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EXPERIMENTAL INVESTIGATION OF FLASHBLINDNESS PARAMETERS

William H. Bowie, et al

Technology, Incorporated

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FINAL REPORT

Contract No. DASA 01-70-C-0007

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Defense Nuclear Agency
Washington, D. C

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TECHNOLOGY INCORPORATED

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FINAL REPORT

EXPERIMENTAL INVESTIGATION OF FLASHBLINDNESS PARAMETERS

This work was supported by the Defense Nuclear Agency under NWER and NWED subtask MB184-01/MB184-02

William H. Bowie and S. C. Collyer

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13. ABSTRACT

An automated flashblindness apparatus was constructed and is described. Various experiments designed to investigate the effect of flashblindness on foveal vision were conducted and are presented. These experiments included: correlation of flashblindness recovery data with fundus reflectometry data; the effect of preadaptation to high ambient light levels on flashblindness recovery time; foveal recovery time as a function of location and area of flash source image; intensity x time relationships; foveal dark adaptation; variability of interindividual flashblindness recovery times and the effect of flash source intensity and duration on recovery times, afterimage brightness and ratio of photopigment bleached.

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FOREWORD

This report was prepared by the Life Sciences Division of Technology Incorporated. The report covers the period of 4 September 1969 to 4 September 1972. During this period Lt. H. J. Mitchell and Lt. Col. J. W. Cable were the contract monitors. This effort was supported by the Defense Nuclear Agency under:

NWER, Subtask MB184, Work Unit Code 01 and

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Acknowledgement is made of the assistance provided by the contract monitors during the period of this study.

The experimental work with volunteer human subjects discussed in this report was conducted in accordance with DOD Instruction 5030.29, 12 May 1964.

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1. BACKGROUND

During the first year of contractual effort, four areas of research interest were designated for investigation. These were listed as follows:

1. Accumulate additional data related to specific flash parameters for improving the current, empirical prediction model, and correlate data between recovery time measurements and the amount of bleached photopigment measured with the fundus reflectometer for the development of the proposed analytical flashblindness model.

2. Investigate the effect of the flash source intensity and duration on recovery times, afterimage brightness, and amount of photopigment bleached.

3. Investigate the effect of the location of the flash source relative to the line of sight on foveal recovery times expressed in terms of the intensity reduction required for a centrally presented flash for the same recovery times.

4. Investigate the effect of preadaption to high ambient light levels on recovery times.

Upon completion of the first year of effort, the following four items were added to the work statement to be completed the second year.

5. Investigate the effect of flash source intensity and duration on recovery times, afterimage brightness, ratio of photopigment bleached and neural

changes occurring.

6. Investigate the effects of foveal recovery times of the location and area of the flash source image, relative to the line of sight for an increased range of flash intensity and duration values.

7. Investigate the effect of preadaptation to a wide range of ambient light levels on recovery times.

8. Perform a population study of the variability of interindividual recovery times to identical flash stimuli and acuity targets.

It is obvious that statement number 4 and statement number 7 are virtually identical. This was shown in a later modification (no. P00001) of the work statement. That modification deleted statement number 2 and 3 above and formally added statement numbers 5, 6 and 8. The work to be performed was then stated as follows:

1. Accumulate additional data related to specific flash parameters for improving the current, empirical prediction model, and correlate data between recovery time measurements and the amount of bleached photopigment measured with the fundus reflectometer for the development of the proposed analytical flashblindness model.

2. Investigate the effect of preadaptation to high ambient light levels on recovery times.

3. Investigate the effect of flash source intensity and duration on recovery times, afterimage brightness, ratio of photopigment bleached and neural changes occurring.

4. Investigate the effects of foveal recovery times of the location and area of the flash source image, relative to the line of sight for an increased range of flash intensity and duration values.

5. Perform a population study of the variability of interindividual recovery times to identical flash stimuli and acuity targets.

On 24 August 1971, Technology Incorporated proposed that the following four items be added to the statement of work to be completed the third year.

6 Record dark adaptation in the peripheral retina following flash exposures identical to those employed in the fundus reflectometry experiments. The size and locations of the exposed and tested areas will be selected to correspond to those employed in the fundus reflectometry program.

7. Extend current work on intensity x time relationships in the parameters of the flash exposure, i.e., to evaluate the visual effectivity of equal energy

flashes of different intensities and durations.

8. Compare the visual recovery times from foveally imaged flashfields presented to one eye and to two eyes.

9. Extend current work on a population study of flashblindness recovery times.

A change in emphasis was requested by Technology Incorporated on 6 March 1972. Statements number 3, 6 and 8 were deleted and in order to be of more direct use to the flashblindness model, the following three statements were added:

1. Record foveal dark adaptation following flash exposures that are identical to those employed in the fundus reflectometer experiments.

2. Record foveal dark adaptation following flash exposures by using gross foveal targets to monitor flashblindness recovery.

3. Investigate the effect of flash source intensity and duration on recovery times, afterimage brightness and ratio of photopigment bleached.

The net result of the various contractual changes listed above was a total of seven tasks as listed below.

1. Accumulate additional data related to specific flash parameters for improving the current, empirical prediction model, and correlate data

between recovery time measurements and the amount of bleached photo-pigment measured with the fundus reflectometer for the development of the proposed analytical flashblindness model.

2. Investigate the effect of preadaptation to high ambient light levels on recovery times.

3. Investigate the effects of foveal recovery times of the location and area of the flash source image, relative to the line of sight for an increased range of flash intensity and duration values.

4. Extend current work on intensity x time relationships in the parameters of the flash exposure, i.e., to evaluate the visual effectivity of equal energy flashes of different intensities and duration.

5. Record foveal dark adaptation following flash exposures by using gross foveal targets to monitor flashblindness recovery.

6. Perform a population study of the variability of interindividual recovery times to identical flash stimuli and acuity targets.

7. Investigate the effect of flash source intensity and duration on recovery times, afterimage brightness and ratio of photopigment bleached.

The methods utilized and results obtained for each of these seven tasks will be presented in the following sections.

2. MATERIALS AND METHODS

2.1 Correlation of Flashblindness Recovery Data with Fundus Reflectometry Data.

In order to compare flashblindness recovery with fundus reflectometer data, the qualities of the bleaching flashes in both experiments were required to be identical. Flash durations of 40 msec and 100 sec were chosen and the retinal illuminance was determined by the method of Westheimer.[1] These illuminance values were adjusted to 9.2×10^{7} td and 9.4×10^{4} td respectively. The total integrated energies of the two flashes were not identical, but were chosen to produce a 70% photopigment bleach, as determined by the generalized five-component model[2] of photopigment kinetics.

The optical system for each apparatus is shown in Figures 1 and 2.

2.1.1 Flashblindness Apparatus and Experimentation

Following a bleaching flash, the subjects were required to judge the orientation of a line target subtending approximately 30' of arc. Eight target luminances were employed resulting in retinal illuminances from 8.9×10^{3} td to 5.2×10^{-1} td.

Three highly experienced subjects were tested over a six week period: the subjects had been used in several previous studies and

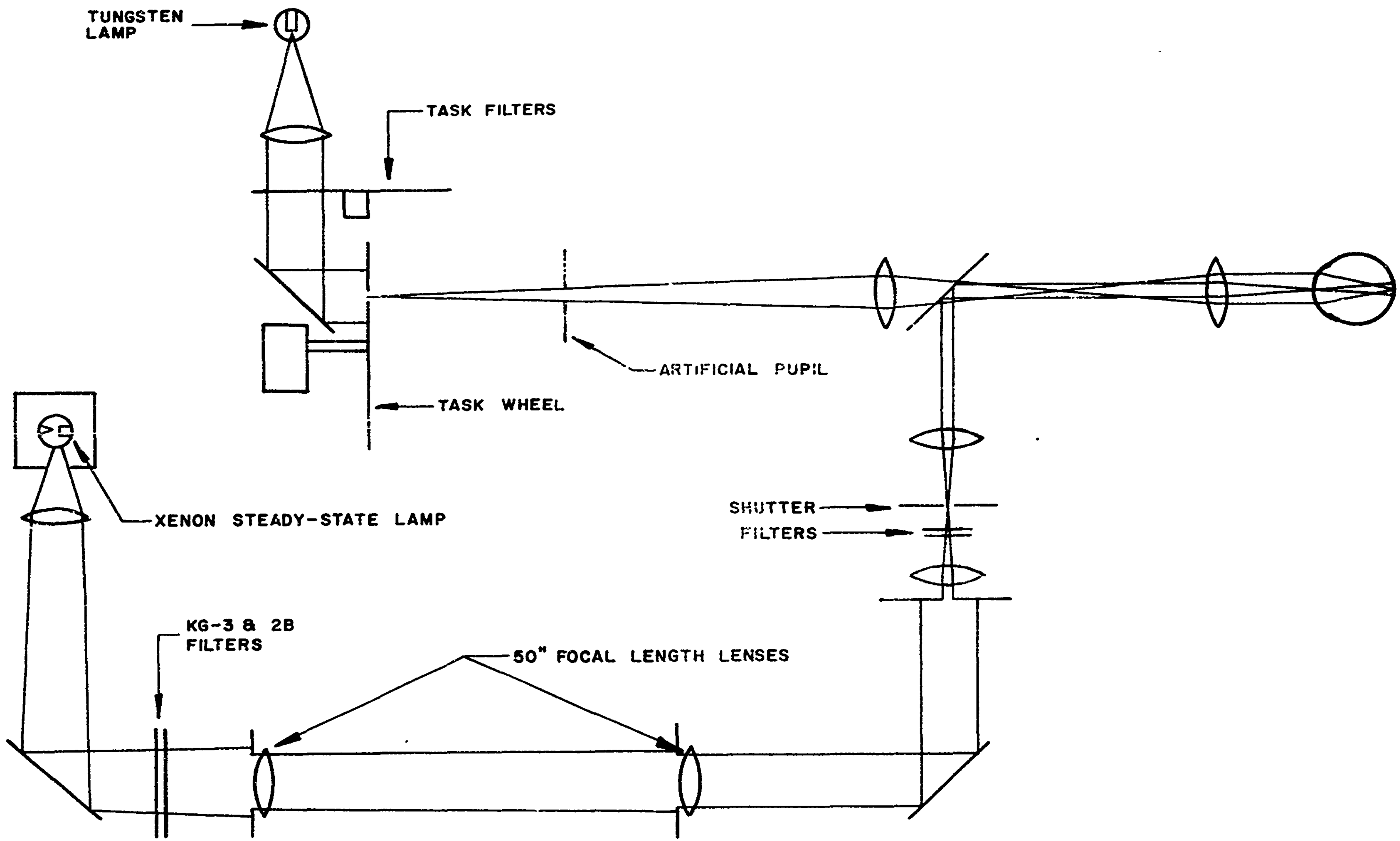

Figure 1. Optical system of flashblindness apparatus used in flashblindness - fundus reflectometry study.

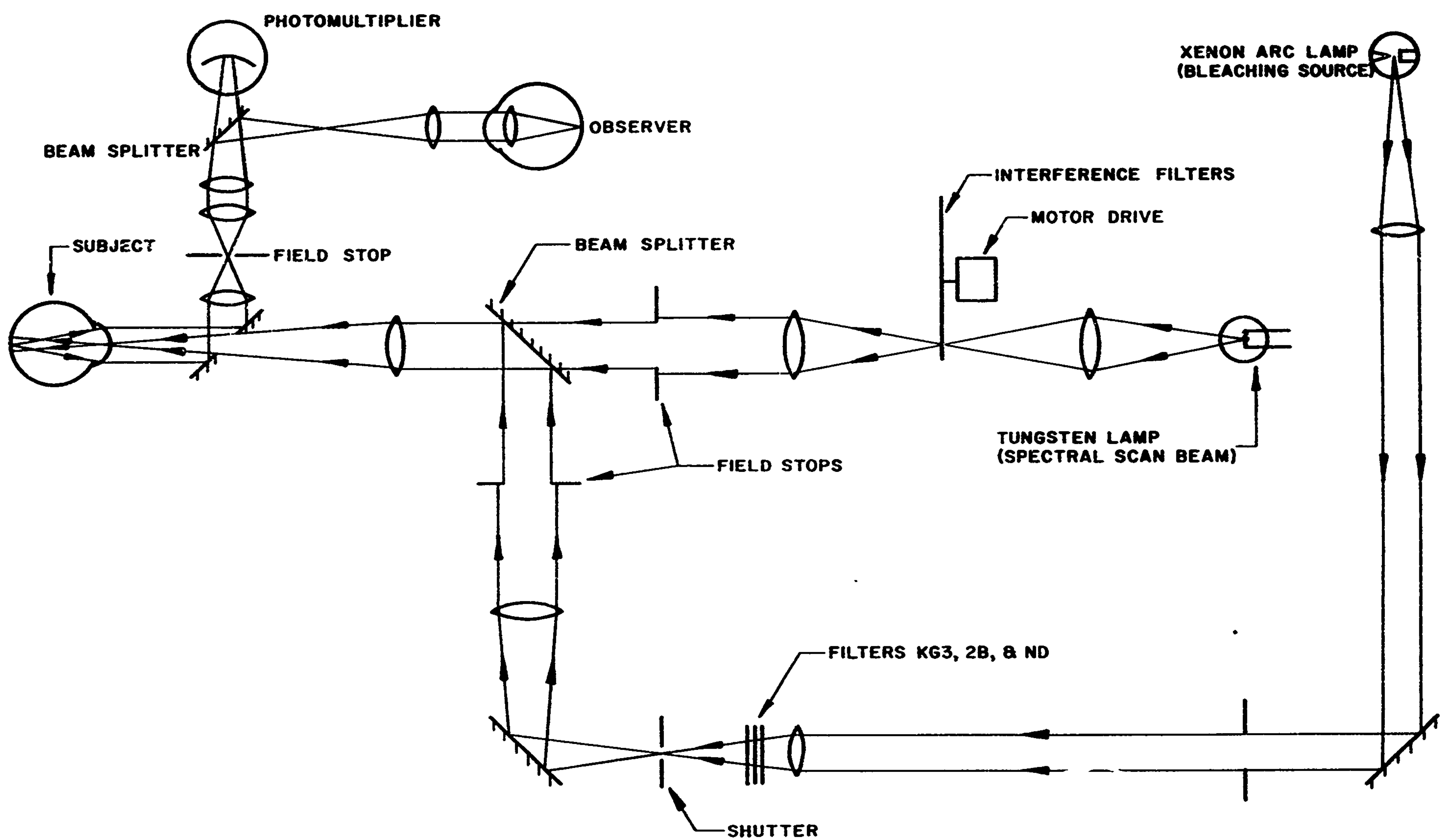

Figure 2. Optical system of the fundus reflectometer.

were skilled in responding rapidly with low error rates. All subjects received at least 20 trials at each exposure level with a ten minute dark adaptation period between each trial.

Six targets were employed, each representing a clock position (i.e., 1, 2, 3, 4, 5 6 o'clock). The subject was seated and instructed to bite firmly on a bite bar made specifically for that subject. He then aligned himself to the optical axis of the apparatus by adjusting the position of the bite bar and thus his head. Alignment was accomplished by viewing a blank field and fixation light and making adjustments of his head position as instructed by the experimenter. When the subject was aligned and dark adapted, baseline data with no flash were obtained by allowing the subject to respond as rapidly as possible to the series of targets. Immediately following the flash, the brightest target was presented to him and as soon as identification was made, one of six keys corresponding to clock positions was pressed. The target then changed in a "random" sequence to a different one of lower luminance. Coincident with the flash a timer was started and the time required to identify each target was recorded. A sequence of eight target identifications was followed to the conclusion of the experimental trial.

2.1.2 Fundus Reflectometer Apparatus

In its final form, the fundus reflectometer was a computerized electro-optical system for the collection and reduction of retinal photopigment regeneration data. A block diagram of the system is presented in Figure 3.

2.1.2.1 The optical system

There were three functional optical pathways in the fundus reflectometer. The first pathway, whose purpose was the production of the measuring beam and the capture of the reflections of this beam from the retina, consisted of a tungsten-filament lamp, a series of lenses and aperture stops for the control of the beam as it entered the eye, a filter wheel containing a maximum of eight narrow-band-pass interference filters, and a collection mirror with an elliptical hole which allowed the measuring beam to pass into the eye while directing the retinal reflections into the photomultiplier tube. The second pathway, which provided the bleaching light for the system, consisted of a high-intensity xenon-arc light source, a system of lenses and mirrors for the control of the beam, a shutter, and a beam splitter to allow the

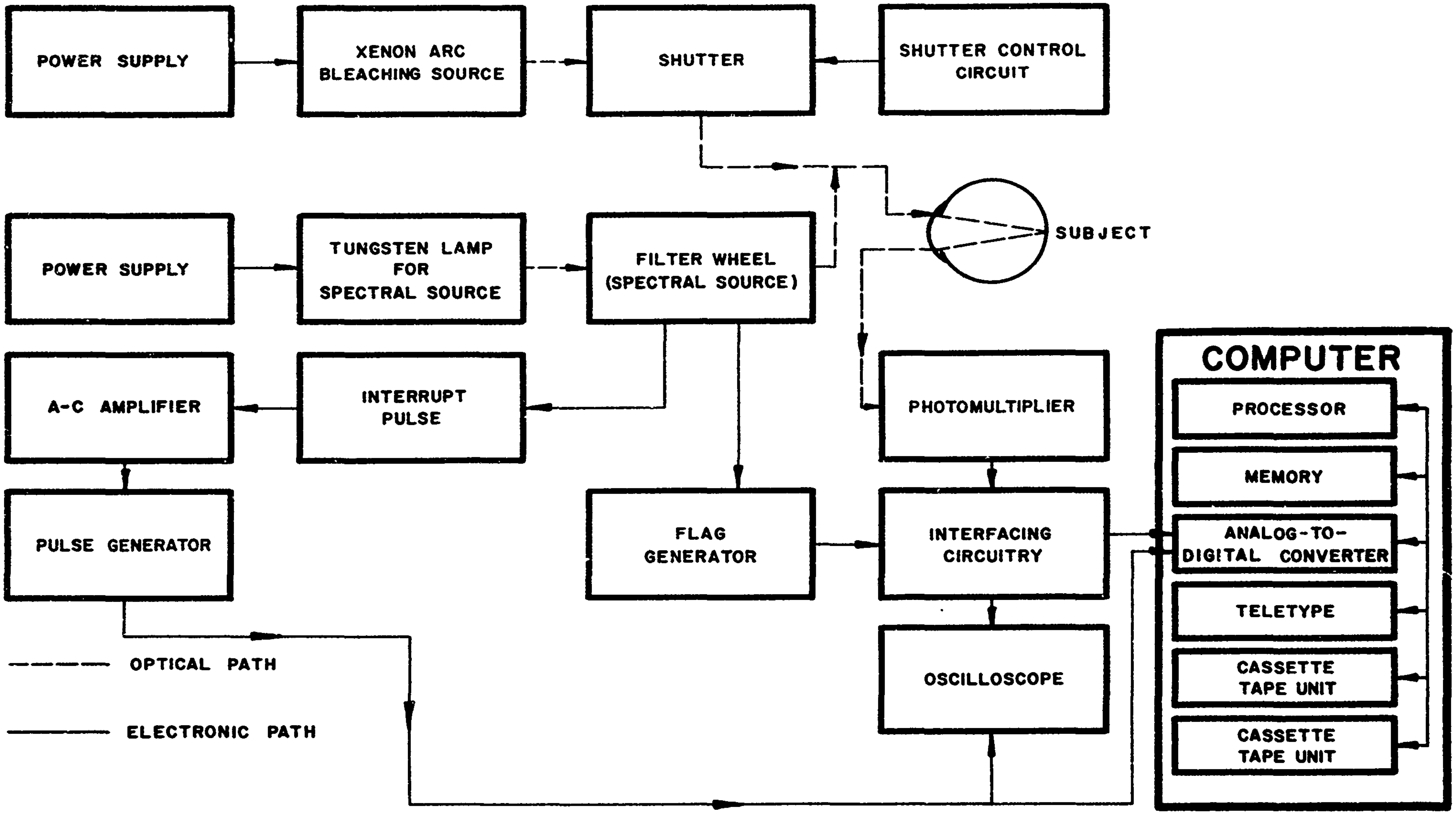

Figure 3. Block Diagram of the Fundus Reflectometer

superposition of this beam onto the measuring-beam pathway. The third pathway performed an ophthalmoscopic function allowing the experimenter to examine the subject's fundus for location and selection of a target area; it consisted of a removable mirror placed at 45^{o} to the optical axis between the collection mirror and the photomultiplier tube, and a series of lenses for magnification of the image.

2.1.2.2 The electronic controls

The electronic controls for the system provided both analog signal-averaging facilities for the reduction of noise in the data output from the photomultiplier tube and pulses for the control of data transmission between the optical system and the computer. The output of the photomultiplier was presented to an operational amplifier which performs signal averaging. On the periphery of the filter wheel was mounted a cam which activated a microswitch once per revolution of the wheel. Closure of this switch presented a signal to a summing input line to the same amplifier. The net result was a large negative-going pulse in the normally positive output

of the amplifier. Also mounted on the periphery of the filter wheel was an annular ring that was opaque except for a series of radially-inscribed slits: one for the cam and one for each filter mounted in the wheel. This ring was positioned between a small light bulb and a photodiode. As the wheel rotated, the slits allowed light from the bulb to reach the photodiode. The output of this photo-diode was connected to an operational amplifier and thence to a pulse generator which shaped and delayed the pulses for system synchronization.

The output of the first amplifier was connected to the data line of the analog-to-digital converter in the computer. This voltage that was treated as data by the system. The output of the pulse generator was connected to the interrupt line of the analog-to-digital converter. The data and interrupt lines were also connected to a dual-beam oscilloscope for real-time monitoring of the data.

The concurrence of a pulse on the interrupt line and positive voltage on the data line was called a "data point": the concurrence of a pulse and negative voltage on the data line

was called a "flag". This flag was used by the computer to maintain synchrony with subsequent cycles of the wheel and was assumed to denote the beginning of a cycle.

2.1.2.3 The computer system

The computer system used to record and process data from the fundus reflectometer consisted of an INTERDATA Model 3 processor with high-speed arithmetic and input/output options; 4,096 sixteen-bit words of core memory; an ASR 33 teletype; two INTERTAPE cassette units with two tape drives each and a single-channel analog-to-digital converter. The A-D converter provided the data interface between the fundus reflectometer proper and the computer. The teletype provided system control via its keyboard and hard-copy output through its printing facilities. The cassette units were used for program and data storage and retrieval.

2.1.2.4 Basic operational characteristics

When all apparatus was readied for an experiment, the filter wheel was turning continuously, thus presenting a continuous train of data points and flags to the analog-

to digital converter. Since it was not possible for the computer to differentiate between these different pulses, provisions were built into the program to allow operator control of the flash-data-flag sequence timing.

Four narrow-band-pass interference filters (666nm, 600nm, 533nm, and 466nm) were mounted in the filter wheel, producing four data points for each cycle of the wheel. The sequence of events resulting from each cycle of the wheel was referred to as a "scan": therefore, in this context, a scan consisted of a flag followed by four data points. The data were recorded in three logical blocks: one set of eight scans was recorded with a dark slide preventing light from reaching the photomultiplier, in order to determine the quiescent voltage of the analog system; one set of eight scans were recorded with the dark slide removed, allowing direct measurement of the dark-adapted state of the fundus; and twenty sets of three scans each were recorded at thirty-second intervals following the flash (i.e., in each thirty second period, three scans were recorded and then twenty-seven scans were skipped). The information recorded on tape as a result of the above procedure was called a "standard run". At the completion

of the experiment, any one of a number of processing programs were loaded into memory at the discretion of the operator to effect analysis of the data, or a subsequent experiment was initiated immediately. The ordinary procedure at the completion of an experiment was to select a simple data printout program to allow determination of data validity and proper recording. Since the data were recorded on tape, more complex processing was ordinarily delayed to allow more efficient utilization of the experiment time available.

2.1.3 Fundus reflectometer experimentation

2.1.3.1 Human experimentation

Experiments were performed using human subjects for flash photolysis and extended photolysis of the foveal region. The subject's left eye was dilated with neo-synephrine Hydrochloride 10%, and then dark-adapted. Measurements were taken using the apparatus to determine the quiescent voltage of the system and the reflectance levels of the dark-adapted fundus. For flash photolysis, the subject was exposed to a bleaching source of 9.2×10^7 td for a period of 40 msec, giving an effective exposure of 3.68×10^6 td-sec. For extended photolysis,

the intensity of the source was 9.4×10^4 td, the duration 100 sec, and the exposure 9.4×10^6 td-sec. These exposure histories were chosen using the theoretical model of photopigment kinetics [2] to give approximately a 70% bleach at the end of the exposure. Experiments in the concurrent flashblindness project were carried out to determine recovery times for identical illuminance-histories to allow comparison of data from the two studies. The measuring beam size, the flash beam size, and the position of the subject were all carefully coordinated to ensure that the area detected by the photomultiplier (approximately 5° - 6° of visual angle) fell within both the area bleached and the area covered by the measuring beam (approximately 10° of visual angle). Subjects were aided in maintaining eye fixation by the interposition of a small black dot in the center of the measuring beam. The photomultiplier tube was protected from exposure to the bleaching source by a dark slide which was removed prior to recording of the regeneration data.

2.1.3.2 Control experiments

Concurrent with the processing of human subjects, a series of experiments was made in which reflectance

was measured from an artificial eye. This artificial eye was designed to approximate as closely as practicable the optical characteristics of the human eye. Mounted at one end of an aluminum housing was a meniscus lens of 1.7 cm focal length; at the other, an aluminum disk with a spherically concave inner surface to which was glued a piece of orange paper. The interior of the housing was lined with black paper to minimize internal reflections. Since the reflectance from the "fundus" (the orange paper) of this device did not change, these experiments provided a valuable tool for determining the ambient noise level of the system as it might affect the outputs of the various processing programs. Monitoring the photomultiplier output during the bleaching exposure with the dark slide in place failed to reveal any light transmission to the photomultiplier. Since no effect on the photomultiplier was observed as a direct result of the bleaching exposure, the inclusion of that exposure in the process of the artificial-fundus experiments was deemed unnecessary, and was omitted.

2.2 The Effect of Preadaptation to High Ambient Light Levels on Flashblindness Recovery Time.

This experiment employed preadaptation retinal illuminance levels of 1.25×10^4, 2.4×10^4 and 7.65×10^4 td. The unit "td" implies that the entrance pupil to the eye was taken into account. However, due to the constrictive properties of the pupil, the actual retinal illumination values varied with each subject and are presented in Table I.

Three experienced subjects were required to view an illuminated field, in Maxwellian view, for about 15 sec. The intensity of the field was then increased ten times by removing an N.D. 1.0 attenuator from the beam, which was viewed by the subject for 10 sec, then reduced back to the original intensity by insertion of the N.D. 1.0 attenuator. After 30 sec. adaptation, at the lower level, the bleaching flash was fired and the field luminance extinguished. In other words, the subject received the flash "on top" of the adapting field, which was there upon extinguished.

The flash source was imaged in the pupil as a 16 mm^2 square and subtended 8^o at the nodal point of the eye. When this was compared to the pupil areas (Table I) it could be seen that there was a flash-pupil limitation for three conditions. The actual retinal illumination was then calculated on the basis of this pupil size and is also given in Table VI (p. 3-10). Eye and head stability was maintained by a fixation light and a dental bite plate respectively and unless stated otherwise this identical system was used throughout the full contractual period.

A second experiment involved presentation of the flash stimulus at various

Table I. Retinal illumination as a function of pupil area.

Subject	Field (td)	Pupil area (mm^2)	Retinal illumination (td)
BW	1.25×10^4	25.0	8.94×10^3
	2.40×10^4	19.5	1.34×10^4
	7.65×10^4	12.6	2.76×10^4
CW	1.25×10^4	34.0	1.22×10^4
	2.40×10^4	31.0	2.12×10^4
	7.65×10^4	27.5	6.00×10^4
JH	1.25×10^4	18.2	6.50×10^3
	2.40×10^4	12.6	8.65×10^3
	7.65×10^4	13.8	3.02×10^2

stages of a period of dark adaptation. In this work, times of 15 sec, 30 sec and 1 min. were chosen for the dark adaptation period. A baseline curve was obtained by exposing the subject to a flash with no intervening adaptation field. An adapting field of 2.4×10^4 td was used in the same manner as above, except for interruptions between it and the flash by the selected dark period. During the dark period, the pupil dilated; consequently, each subject received the same retinal illuminance from the flash.

In order to expand the adaptive range covered by the contrast resolution targets in both experiments, an additional 1.0 neutral density attenuator was placed in the task beam. This produced task luminance values stepped down by a factor of 10 from the original values.

2.3 Foveal Recovery Time as a Function of Location and Area of Flash Source Image.

2.3.1 Recovery time as a function of flash field location

Four subjects were tested, each at nine flash locations, for an average of ten, one hour experimental sessions per subject. A schematic diagram of the apparatus used is presented in Figure 4.

The flash source utilized was circular, its diameter subtending 6.2° of arc at the eye, and positioned so as to provide: (a) a central, foveal flash; (b) flashes centered 2.9° from the fixation point and located at 90° intervals about the fixation point; and (c) peripheral flashes located at the same 90° intervals, but centered 5.8° from

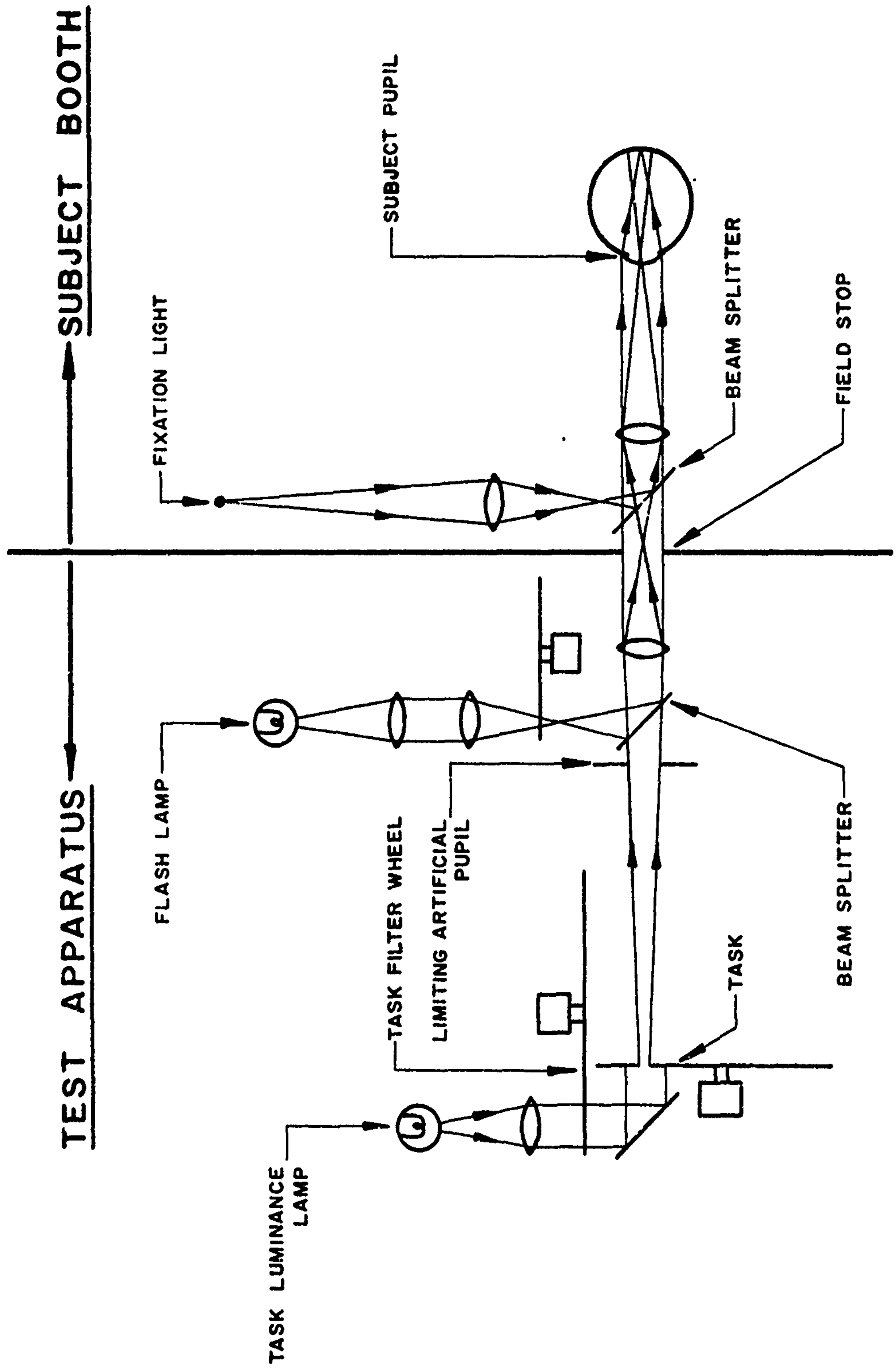

Figure 4. Flashblindness apparatus used in use for fixation studies.

the fixation point. The flash distance from the point of fixation was chosen so that the off-center flashes barely overlapped the fixation point. For the more peripheral flash fields, the fixation point was approximately 2.7° from its nearest edge of the flash area. The flash field was not imaged upon the optic nerve head when presented in the temporal 3 o'clock position.

Following a flash, a standard target identification task was employed. This involved the identification of transilluminated Snellen 20/40 letters at successively decreasing luminance levels. Due to the positioning of the flash relative to the point of fixation, identification of the letters was accomplished by looking through the resulting afterimage in the case of the central and off-center flashes, and around the afterimage for the most peripheral flashes. Figure 5 illustrates the location of the afterimage relative to the foveally-fixated target letter for the nine flashes.

The retinal flash exposure used was 5.7×10^{6} td-sec throughout this experiment; with an equivalent exposure time of 0.5 msec. The acuity target luminances ranged from 108 fL to 0.54 fL.

2.3.2 Recovery time as function of flash image size.

A freely viewed flash was used to simulate the worst-case flashblindness condition, i.e., foveal exposure.

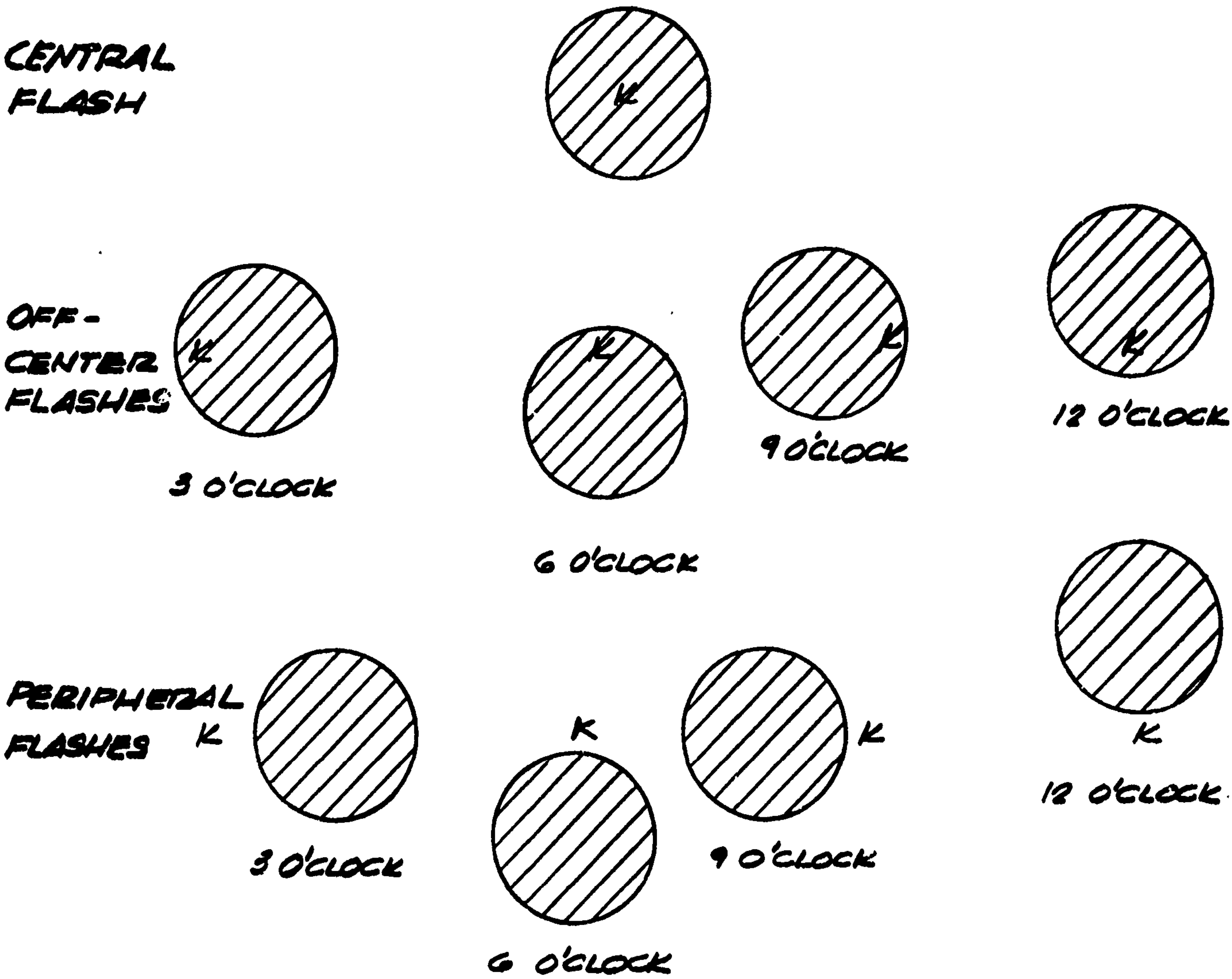

Figure 5. Approximate location of the afterimage relative to a centrally fixated target letter (K), for the nine flash positions.

The flash source was a Honeywell 65C flash unit with a diffuser placed over the front of the reflector and masked to provide a uniform circular source 2-inches in diameter. The resulting retinal illuminance was maintained at 6.30×10^5 td-sec for the following work. The pulse shape and time course of the flash are shown in Figure 6 .

This recovery task was a series of dark letters on a light background presented at 20/40 Snelien acuity by a Clason projector. Neutral density attenuators were inserted in the projector beam to control the luminance level of the task background and hence, the visual contrast level. Flashes from 1° to 4.5° were initially investigated by this method. This was later extended to 5°.

In a typical experiment, the subject was seated and dark adapted. A dim light was trained upon the flash source and the subject was asked to fixate on the center of the sources. Immediately after the flash had been presented, the subject turned on the Clason projector and attempted to identify the letter presented. Upon identification of the letter, the subject was questioned as to his method of identification, i.e., around or through the afterimage. The identification time and method were recorded and a new letter was positioned in the projector. Letters were presented in a random order without the subject's prior knowledge of the identity of the letter.

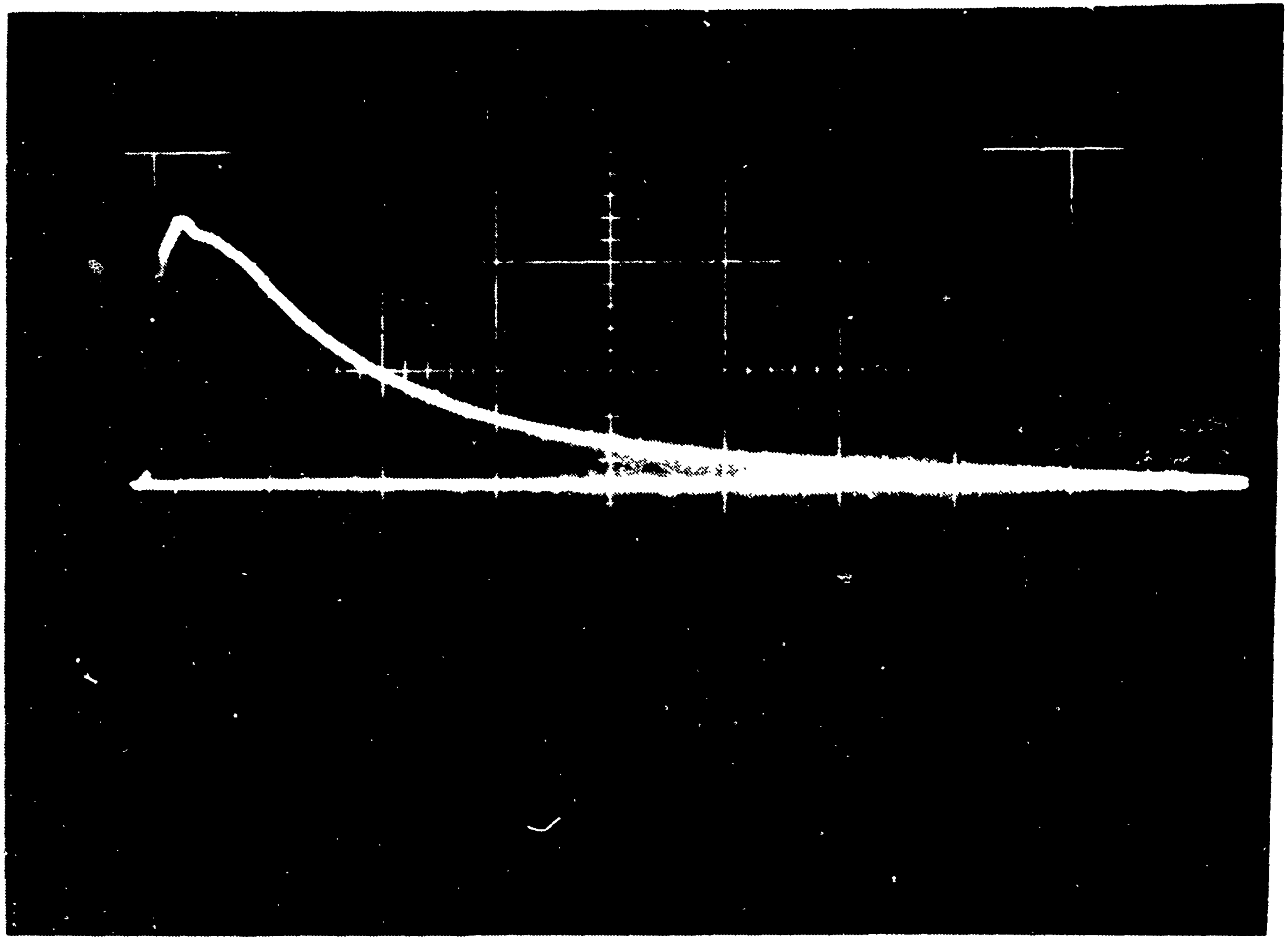

Figure 6. Honeywell 65C flash pulse and time course. Sweep equals 0.2 msec per cm.

2.4 Intensity x Time Relationships

Three flashes of equal time-energy relationships were studied in the first phase of this experiment. These were 0.5, 0.76 and 1.44 msec. A second series of experiments utilized times of 0.5, 5.0, 13.3 and 40 msec. The final series of experiments utilized flashes of 0.5, 13. 100 and 1000 msec. These were designed to produce flashes of equal energy and to test the effect of the delivery of this energy to the retina in the specified times.

A second experiment was conducted in which the object was to bleach the same amount of photopigment, regardless of the flash used. In this work two exposures of 0.5 msec and 120 sec were utilized.

2.4.1 Equal energy exposures

The flash field (3.9×10^6 td-sec) subtended 10° at the eye and was centered about the fovea. The area of the flash field on the retina was controlled by an appropriately sized field stop placed in the primary focal plane of the lens providing a Maxwellian view to the subject's eye.

All contrast threshold targets subtended 0.6° at the eye and were fixated centrally so that observation through the afterimage during flashblindness recovery was unavoidable.

The subjects were each dark adapted for 10 minutes prior to the first

flash recovery run, and for periods of 5 minutes between successive flashes. The duration of the initial dark adaptation period was not critical, because the recovery data from the first flash was discarded in analysis. Flashes of equal energy but of various duration (see above) were presented to the subject in a random fashion.

In order to extend the flash exposures into the second series of experiments an additional optical system and lamp were required. A 2500 watt xenon lamp was mounted at one end of the laboratory. An optical pathway was constructed and mounted along one wall of the laboratory in order to direct the light into the existing apparatus and the subject's eye. The system is shown in Figure 1.

The third series of experiments was conducted in a manner similar to the former two series. Durations of 0.5, 13, 100 and 1000 msec were employed, each having the same total integrated luminous flux (3.9×10^6 td-sec) as the previous experiments. However, only four contrast threshold targets (20/80 Snellen letters) were employed for this particular experiment.

2.4.2 Equal bleach exposures

This study consisted of a comparison of flashblindness recovery times following a 1.5 msec flash, at an intensity of 1.0×10^9 td, and a 120 sec steady exposure, at 3.5×10^4 td. By means of a two-component

model of photopigment kinetics [3], both exposures were initially calculated to result in a 40% photopigment bleach in a previously dark adapted eye. In these calculations a regeneration time constant of 60 sec was initially chosen for the steady exposure; however, a more appropriate time constant of 120 sec [4] predicts a 52 % bleach for this exposure.

The high-intensity xenon arc lamp previously described was used for both exposures; durations were controlled by means of an electronically controlled shutter. The exposure field was circular and subtended 6.2° of arc at the eye. All exposures were centered upon the fovea.

Four trained observers were utilized for a total of six 2-hour sessions. Each session consisted of a total of ten baseline (no flash) trials, and five flash trials alternating with five steady-exposure trials. Since earlier work from this laboratory demonstrated that a considerable learning effect exists [5], the first two sessions were considered practice, and were eliminated from the analysis.

The standard experimental procedure was followed, in which, following the flash the subject identified a series of Snellen 20/40 letter targets of decreasing luminance. The time required to correctly identify each letter was recorded, along with the total number of errors made on each trial. The detection of errors was a late addition to the

automated flashblindness apparatus, and provided a useful means of assuring that subjects maintained a reasonably consistent criterion for letter identification across all experimental conditions. A seven-minute period for dark adaptation was provided between trials (except for baseline trials, which were separated by 30 sec intervals).

A second phase of this work differed in several procedural respects from that previously conducted. The principal changes were as follows:

(1) A new set of identification targets was prepared, in order to study the effects on recovery time of targets of lesser complexity. In contrast with the previously used targets (Snellen 20/40 letters), each of these targets was a single line, subtending approximately 30' of arc, with a length/width ratio of 12/1. On each identification trial the target appeared in one of six orientations. When the subject was able to see the target, he pressed the button corresponding to its orientation, and his response time was recorded automatically. A new target orientation was then automatically presented, and the luminance was decreased by the addition of a neutral density filter.

(2) The range of target luminances was increased, in order to study the recovery function over an increased temporal span. Previous work incorporated seven retinal illuminance values ranging from 422.1 to 1.64 td. The present study utilized eight illuminance levels from

8,900 to 0.52 td.

(3) Although the exposure histories chosen were identical to those reported earlier in this section (1.0×10^9 td for 1.5 msec; and 3.5×10^4 td for 120 sec), a procedure was devised that permitted monitoring these exposure levels at intervals throughout the experimental session. This procedure resulted in decreased variability of exposure level from trial to trial, caused by fluctuations in the output of the xenon arc lamp.

A total of three subjects were tested repeatedly over a five-week interval. All were given a sufficient number of practice sessions to ensure stable performance.

2.5 Foveal Dark Adaptation

The targets previously used in most flashblindness research at this laboratory consisted of Snellen letters, resulting in a complex pattern recognition task. In contrast, the targets used in a portion of this experiment consisted of a single line subtending approximately 30' of arc with a length/width ratio of 12/1. Two experiments utilizing three bleach exposures were conducted to study dark adaptation with these particular targets. The exposures were: 40 msec (70% bleach), 100 sec (74% bleach) and 120 sec (52%bleach). The experimental procedure and subject reactions were standard and are described in section 2.1.1.

2.6 Variability of Interindividual Flashblindness Recovery Times

Two types of experiments were involved in the study of population variability. One set of experiments was primarily designed to probe intrasubject variability and variability across relatively few (5) subjects. The second experiment utilized a freely viewed flash and ten subjects. Three similar experiments were involved in the intrasubject and "small sample" study. Pertinent parameters of these experiments are given in Table II.

All subjects involved in the intrasubject and "small subject" study were highly trained and were performing complex task for which their training had been specific. The methods and procedures followed in these experiments were standard and have been described in general in Section 2.1.1.

The freely viewed flash experiment has been previously described in Section 2.3.2. Most of the subjects utilized for this experiment were inexperienced and available for only a few trials, therefore, it was felt necessary to keep the task as simple as possible. The free viewing system and letter projection seemed to fulfill these requirements.

2.7 The Effect of Flash Source Intensity and Duration on Recovery Times, Afterimage Brightness and Ratio of Photopigment Bleached.

This task encompassed a large part of the total contractual effort and can be handled most conveniently by presenting it as three separate tasks.

TABLE II

Parameters of Intersubject and "Small Sample" Study

Report No.	No. Ss	FRI[1]	Exp. Time(sec)	NRPT[2]	TRIR[3]	Target
14	4	$1.0x10^9$	0.0015	78	$4.2x10^2 - 1.65x10^0$	letters
		$3.5x10^4$	120.0	76	$4.2x10^2 - 1.65x10^0$	letters
15	3	$1.0x10^9$	0.0015	66	$8.9x10^3 - 5.2x10^{-1}$	line
		$3.5x10^4$	120.0	69	$8.9x10^3 - 5.2x10^{-1}$	line
16	3	$1.8x10^6$	0.04	64	$8.9x10^3 - 5.2x10^{-1}$	line
		$9.2x10^7$	0.04	69	$8.9x10^3 - 5.2x10^{-1}$	line
		$9.4x10^4$	100	68	$8.9x10^3 - 5.2x10^{-1}$	line

(1) FRI = Flash Retinal Illuminance

(2) NRPT = Number of Responses per Target

(3) TRIR = Target Retinal Illuminance Range

2.7.1 The effect of flash source intensity and duration on recovery time.

Recovery times following a bleaching flash depend upon several things in addition to the flash source intensity and duration. Some of these are flash field size, task luminance and size, and state of light adaptation at the time of the flash.

The term "reciprocity" has been used to describe the effect obtained from flashes of equal integrated energy. This effect was intensively investigated using the methods presented in Section 2.4. In addition to the results obtained from this work, certain inferences may be made from other data collected during the contract effort. These will be presented in section 3.4. In all cases, the materials and methods have been presented in section 2.4.

2.7.2 The effect of flash source intensity and duration on afterimage brightness.

The scope of this work encompassed both monocular and binocular viewing of a bipartite field. The afterimage occupied one-half of the center visual field and the juxtaposed matching field, occupied the other half. A calibration of the matching field (Figure 7) showed a brightness range of approximately seven log units through the crossed density wedges. The entire device, for both monocular and binocular work is shown digrammatically in Figure 8

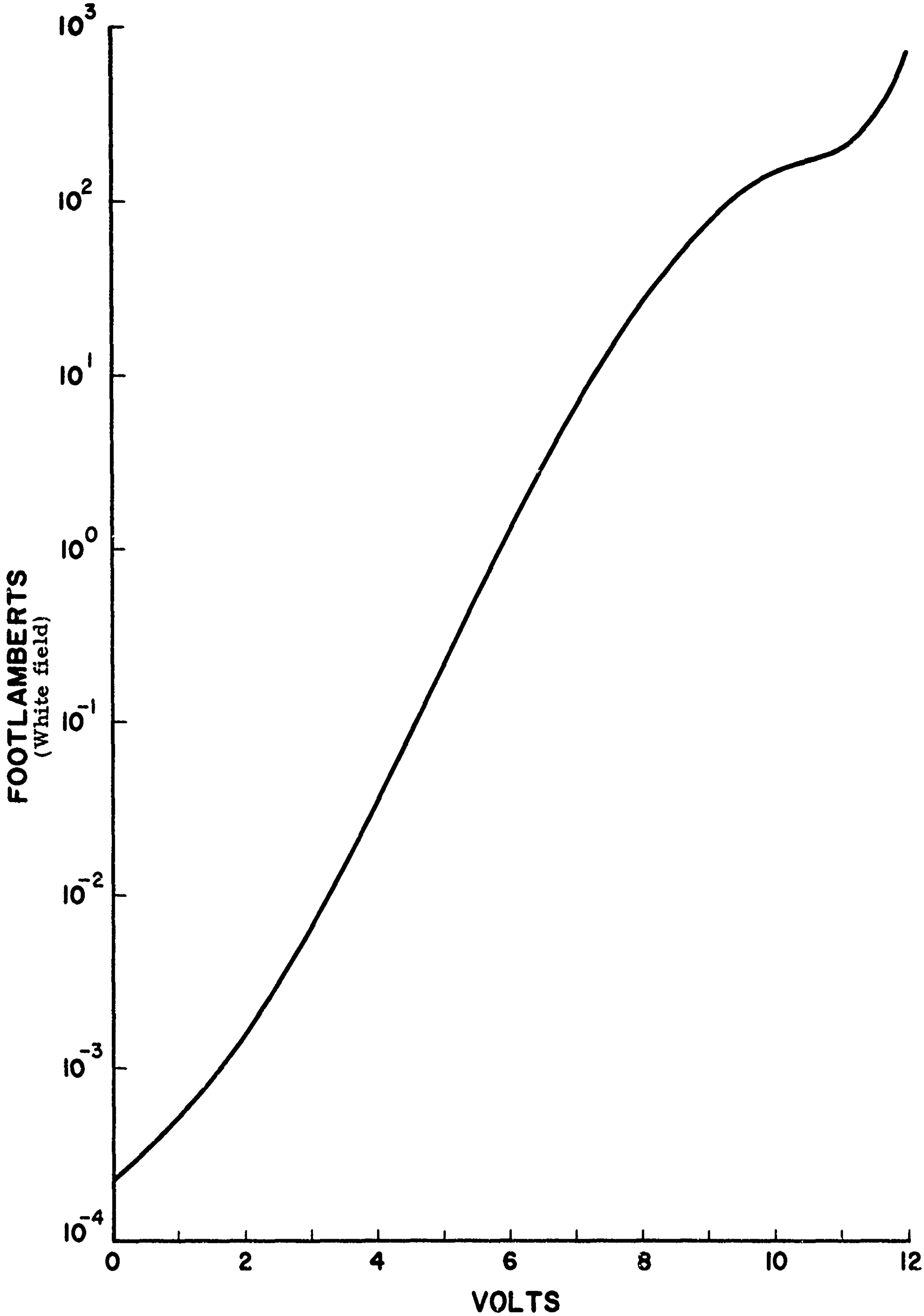

Figure 7. Calibration curve of matching field intensity vs potentiometer reading of wedge position.

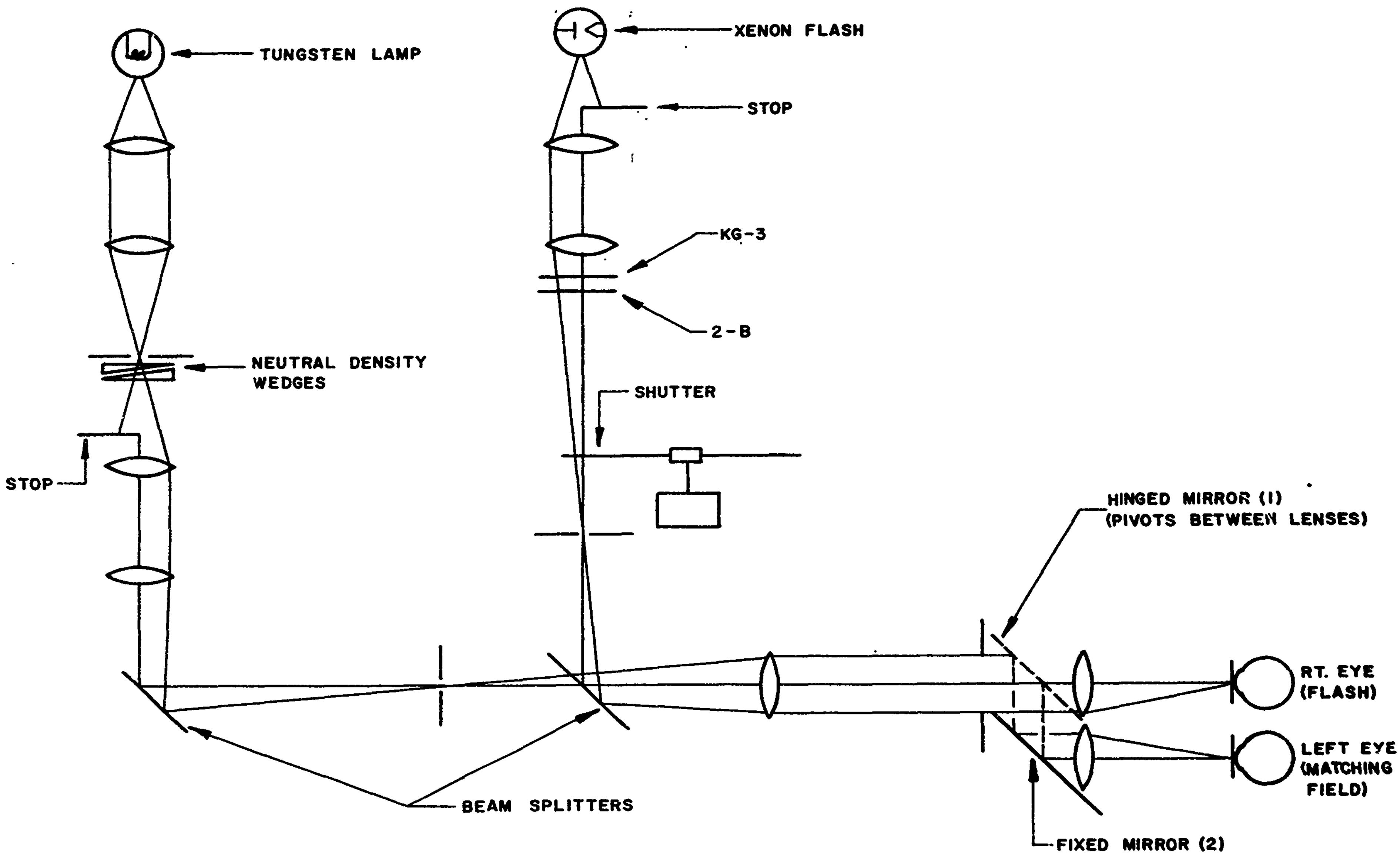

Figure 8. Flashblindness device used in monocular and binocular matching of afterimage brightness.

A total of four subjects were run. It was not possible to perform the same number of experiments or the same type of experiments on all subjects. The subject's task in both phases of this experiment was to control the brightness of one side of the split field and match that brightness to the brightness of the afterimage. This was done by operation of a rocker switch. Pressing one side of the switch brightened the field while pressing the other side dimmed the field.

2.7.2.1 Monocular matching test program

Each subject was required to dark adapt for 10-15 minutes in a totally dark room. He was then requested to fixate on a dim red dot which was situated on the dividing line between the two halves of the bipartite field. The subject could see only the red dot on a uniformly dark field. When ready, he received the flash in the left half of the field. This produced a reversed "D" shaped afterimage. The matching field was illuminated simultaneously with the flash and was presented to the same eye.

Several runs were made with an ND 1.0 altenuator in the flash beam. This lowered the flash exposure to about 2.7×10^6 td-sec.

2.7.2.2 Binocular matching test program

It is obvious that intraocular scatter and lateral neural interactions will tend to desensitize the retinal areas near which a target is imaged. This desensitized area may appear as an afterimage of some equivalent brightness.

In order to measure this equivalent brightness independent of bright matching fields, the binocular matching mirrors in Figure 8 were installed. The experimental protocol was virtually identical to that of the monocular studies. The only difference was when the subject received the flash in his right eye, he pulled a line attached to a mirror (No. 1 in Figure 8). This shifted the matching field into the left eye and blocked any light from reaching the right eye. The mirrors indicated in Figure 8 were aluminum coated first surface mirrors of approximately 84% reflectance. This reflectance coefficient is accounted for in the results.

2.7.3 The effect of flash source intensity and duration on the ratio of photopigment bleached.

All experimental protocol pertaining to this experiment has been described in detail in previous sections and in general in Section 2.7.1. Table III lists the experiments and parameters utilized for this study.

TABLE III

Flash Parameters Pertinent to a Study of the Effect of Flash Source Intensity and Duration on Ratio of Photopigment Bleached

Report No.	Retinal Illuminance (td)	Flash Pulse
3	2.38×10^{10}	0.8 msec
	2.9×10^{11}	0.8 msec
6	7.8×10^{9}	0.5 msec
	3.0×10^{8}	13.0 msec
	3.9×10^{7}	100.0 msec
	3.9×10^{6}	1000.0 msec
7	4.12×10^{8}	5.0 msec
	6.5×10^{7}	5.0 msec
	4.12×10^{7}	5.0 msec
	4.2×10^{7}	5.0 msec
8, 9, 10	$.126 \times 10^{9}$	0.5 msec
10	1.14×10^{10}	0.5 msec
14, 15	1.0×10^{9}	1.5 msec
	3.5×10^{4}	120 msec
16	9.2×10^{7}	40 msec
	1.8×10^{6}	40 msec
	9.4×10^{4}	100 sec

3. RESULTS

3.1 Correlation of Flashblindness Recovery Data with Fundus Reflectometry Data

Identical flash exposures were necessary to correlate data from these two experiments. Two exposure durations were used: 40 msec and 100 sec. According to the generalized five-component model of photopigment kinetics[5], each exposure, at the proper intensity, should bleach 70% of the available photopigment. Average flashblindness recovery times for this bleach level are shown by two curves in Figure 9 (9.2×10^7 td and extended exposure) as a function of target retinal illuminance.

Ten sessions were conducted with the fundus reflectometer at each of the two bleaching intensities. In addition, several control runs were made utilizing an artifical eye. The optical density difference of each set of data was calculated and is displayed with the human eye data in Figure 10and11 .

Optical density differences (Δ OD) were calculated according to the following equation:

$$\Delta OD = \text{Log}_{10}\,((Vp/Vpr)/(Vb/Vbr))$$

Where: Vp = a data point from a post-flash scan
Vpr = the 666nm point in that scan
Vb = a data point from the baseline scan
Vbr = the 666nm point in that baseline scan

The data from the artifical fundus are essentially linear with time and

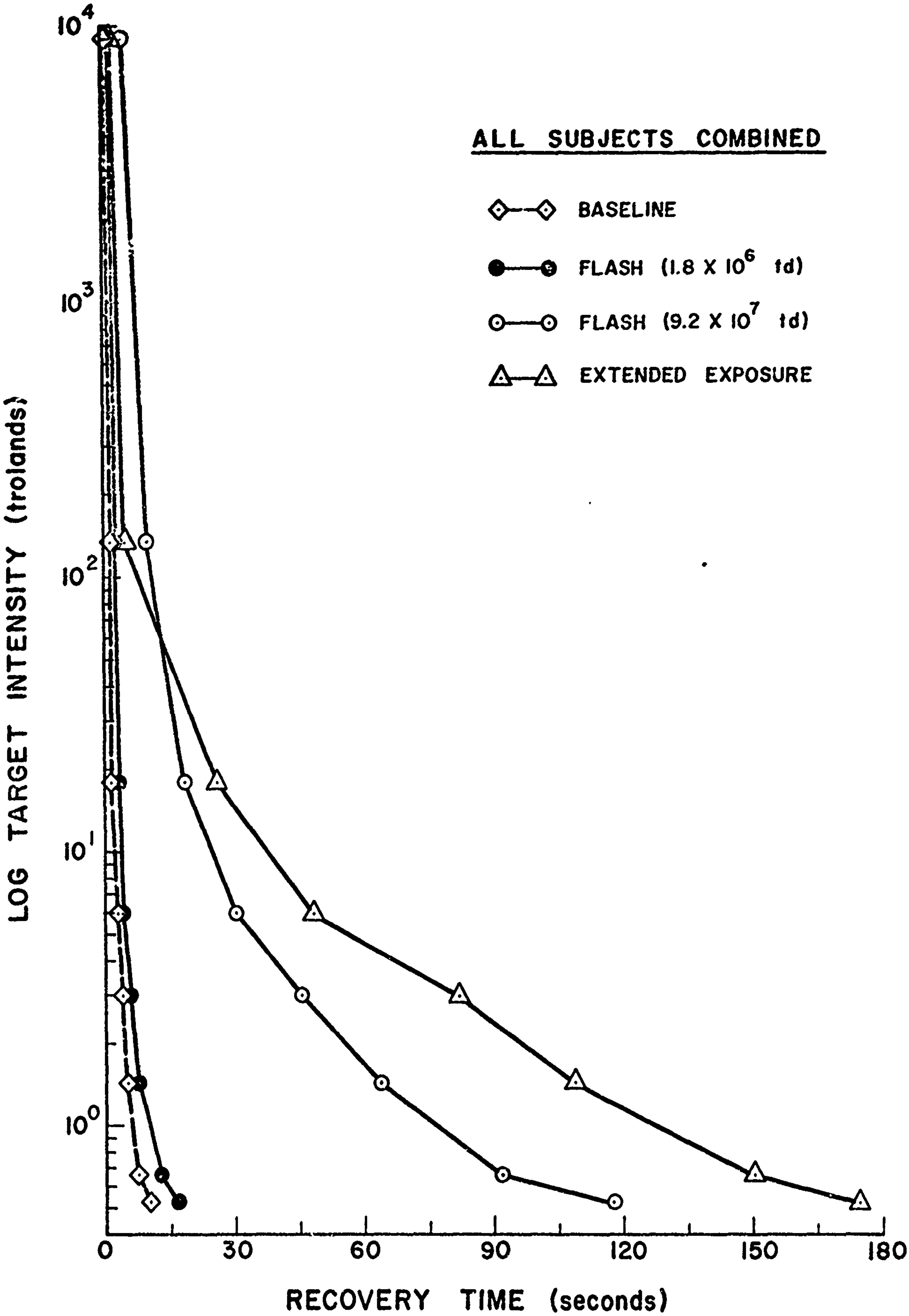

Figure 9. Flashblindness recovery as a function of target retinal illuminance following flash exposures as indicated.

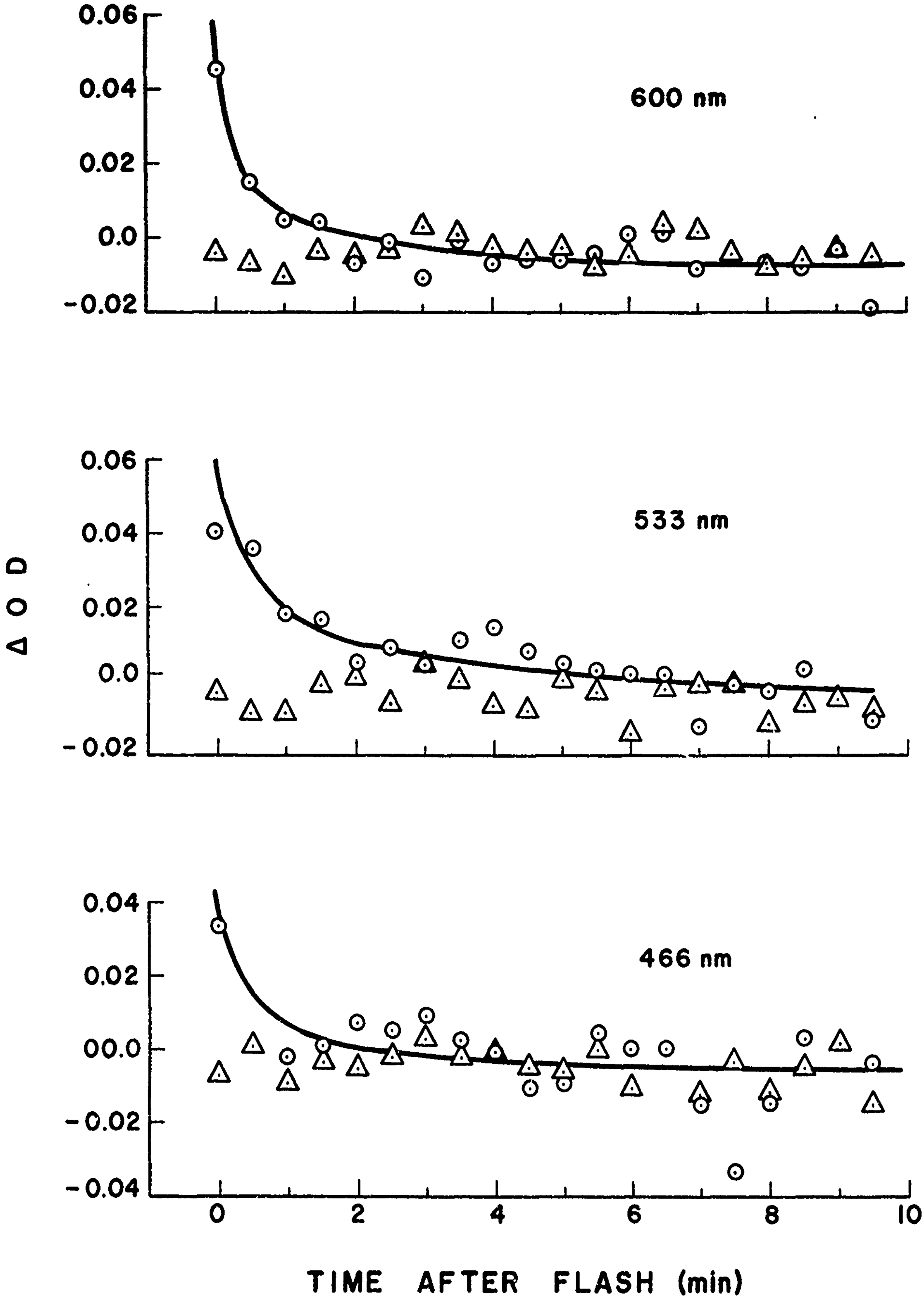

Figure 10. Optical density differences as a function of the measuring wavelength following a 40 msec flash exposure.

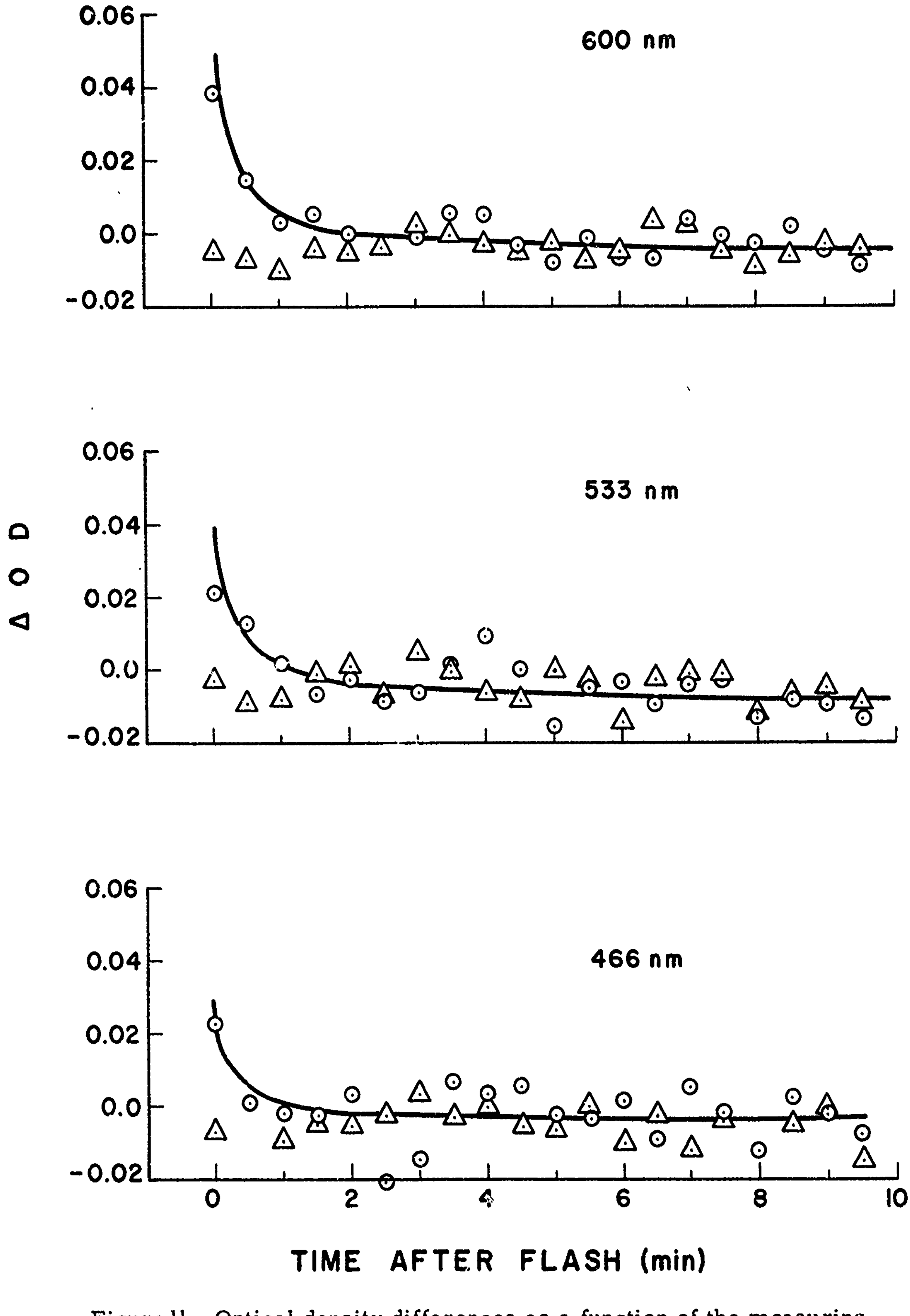

Figure 11. Optical density differences as a function of the measuring wavelength following a 100 sec light exposure.

remained very close to zero. The optical density differences calculated from the human experiment data were as expected, in that they showed a high Δ OD immediately after the flash followed by a decrease toward zero. The magnitude of the differences obtained with this system is somewhat lower than that of Weale[6], however, the data do show that the system was correctly measuring reflectance changes in the human retina during the regeneration of photopigments.

It will be noted that the curves in Figure 10 and 11 start at 0 time but this was not actually the case during the experiments. Occasionally, as much as 5 sec elapsed before the recording apparatus could begin taking data. This amount of time cannot be conveniently shown on the scale selected for the figures, so each curve is shown to start at 0 time. Figure 10 and 11 were referred to for the points used to construct the smooth curves in Figure 12. Both flashblindness recovery times and Δ OD as a function of time are shown here. It should be remembered that the higher the Δ OD the greater the amcunt of pigment bleached. It was also assumed that the higher the flashblindness target values for a given time, the brighter the afterimage and the more photopigment bleached.

3.2 Effects of Preadaptation to High Ambient Light Levels on Flashblindness Recovery Time

The right eye of three subjects was adapted to calculated retinal illuminances of 1.25×10^4, 2.4×10^4, and 7.65×10^4 td. However, a study of

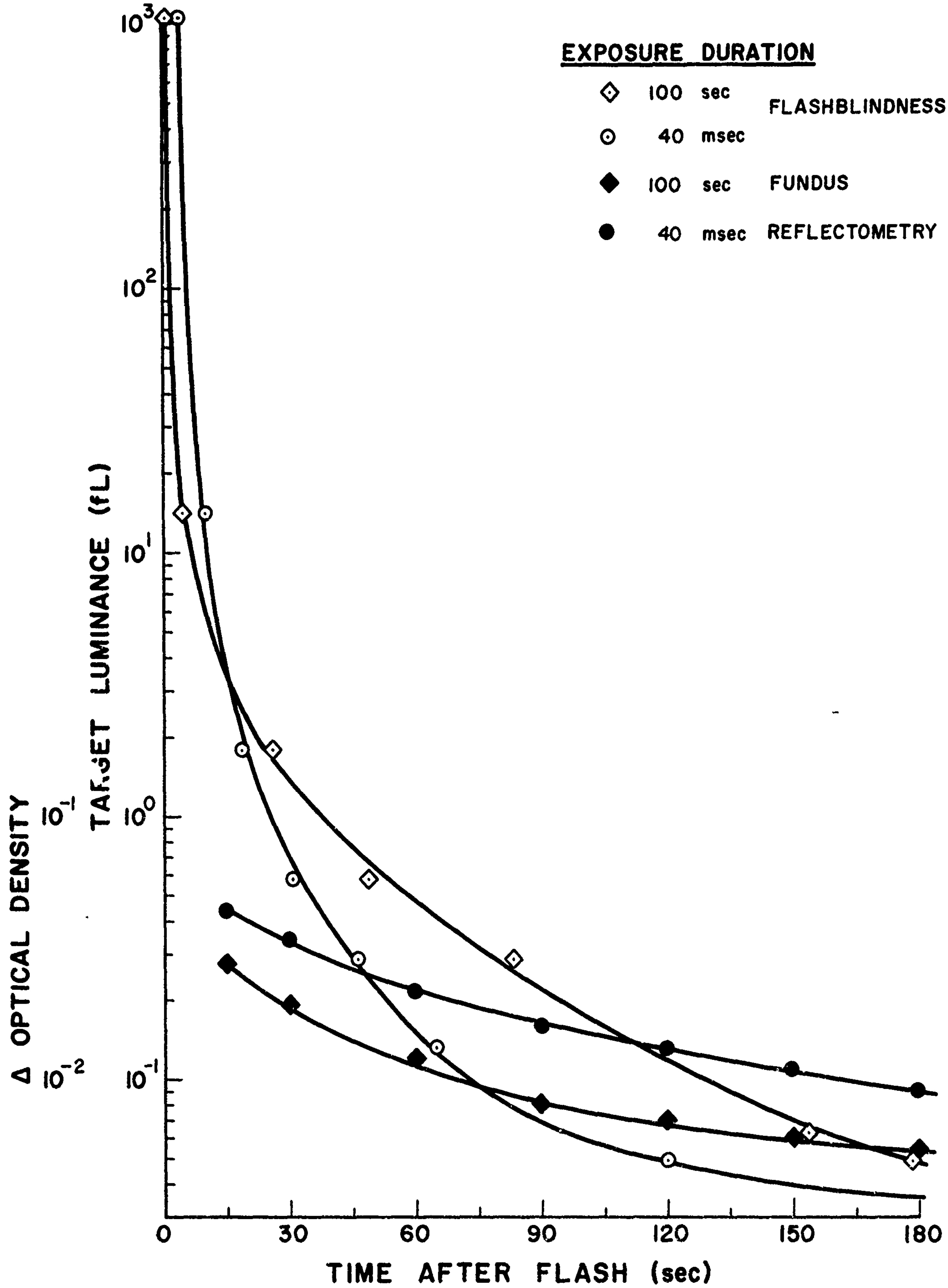

Figure 12. Comparison of flashblindness recovery and Δ OD (533 nm) from fundus reflectometry.

pupil contraction revealed the values listed in Table I for the respective subjects. Due to vignetting caused by the contracted pupil, several subjects received a retinal illuminance of 1.9×10^7 td-sec (2.38×10^{10} td). The remainder received the full retinal illuminance of 2.3×10^7 td-sec (2.88×10^{10} td). Addition of the adapting field illuminance and the flash illuminance resulted in a rather insignificant increase in total retinal illuminance which has been reported as retinal exposure in Table IV and V. Table VI lists the photopigment bleach values of the adapting fields before and after the flash. Little or no difference was noted between recovery curves following the various adapting-flash exposures. Consequently, the data were presented in Figure 13 as one recovery curve along with the baseline (flash only) condition.

3.3 Foveal Recovery Times as a Function of the Location and Area of the Flash Source Image

3.3.1 Recovery time as a function of flash field location

An experiment was conducted which was designed to investigate the effects of retinal flash location on flashblindness recovery times. The flashes were centered 2.9° and 5.8° from the fovea. A schematic diagram of the equipment utilized in this experiment is shown in Figure 4 .

Due to the positioning of the flash relative to the point of fixation,

Table IV. Mean recovery times as function of retinal exposure.

1.9×10^7 td sec

Task fL	Subject JH	Subject BW	Subject JH	$\overline{X}$
520	4.5	4.5	4.2	4.4
185	5.3	5.4	5.1	5.3
56	6.2	5.6	5.6	5.8
23	8.0	8.4	8.5	8.3
18	7.2	7.2	6.7	7.0
10	8.8	11.1	10.2	10.0
8.3	9.4	11.9	12.2	11.2
5.9	8.2	8.9	7.9	8.3
4.7	11.8	14.0	15.5	13.8
2.4	12.5	14.9	17.1	14.8
1.0	15.8	15.3	18.9	16.7
0.83	18.3	20.3	21.8	20.1
0.47	31.6	24.7	40.5	32.3
0.24	35.4	35.1	51.2	40.6

Table . V. Mean recovery times as a function of total retinal exposure.

2.3×10^7 td sec

Task fL	Subject JH	BW	BW	CW	CW	CW	$\overline{X}$
520	5.0	4.0	4.0	3.6	4.2	4.0	4.1
185	5.8	5.0	5.3	4.7	5.3	5.2	5.2
56	6.2	6.1	6.4	5.7	6.5	6.3	6.2
23	8.0	7.4	7.7	7.4	8.3	7.5	7.7
18	6.8	7.0	7.8	6.8	8.4	8.2	7.5
10	9.0	9.5	9.6	8.6	9.6	9.2	7.8
8.3	10.1	11.4	10.7	9.7	10.6	10.7	10.5
5.9	8.0	8.4	9.4	12.2	13.9	11.0	10.5
4.7	12.2	13.5	12.4	13.2	13.6	12.1	12.8
2.4	13.1	14.9	16.0	14.8	16.7	14.3	15.0
1.0	17.8	17.1	21.6	23.4	28.9	21.1	21.6
0.83	20.2	22.0	25.2	25.1	26.1	23.8	23.7
0.47	26.6	27.1	34.0	33.5	37.7	39.4	33.1
0.24	34.4	34.4	38.2	43.4	44.4	49.1	40.6

Table VI. Photopigment Bleach as a Function of Retinal Illumination

Subject	Adapting Field(td)	%Bleach	Flash (td) @0.8 msec	%Bleach	Adapting Field Bleach + Flash Bleach
JH	8.65×10^{3}	11.38	2.38×10^{10}	99.81	99.84
	3.02×10^{2}	0.45	2.38×10^{10}	99.81	99.81
BW	2.76×10^{4}	29.07	2.38×10^{10}	99.81	99.87
JH	6.50×10^{3}	8.80	2.88×10^{10}	99.95	99.95
BW	8.94×10^{3}	11.72	2.88×10^{10}	99.95	99.96
	1.34×10^{4}	16.60	2.88×10^{10}	99.95	99.96
CW	1.22×10^{4}	15.34	2.88×10^{10}	99.95	99.96
	2.12×10^{4}	23.94	2.88×10^{10}	99.95	99.96
	6.00×10^{4}	47.12	2.88×10^{10}	99.95	99.97

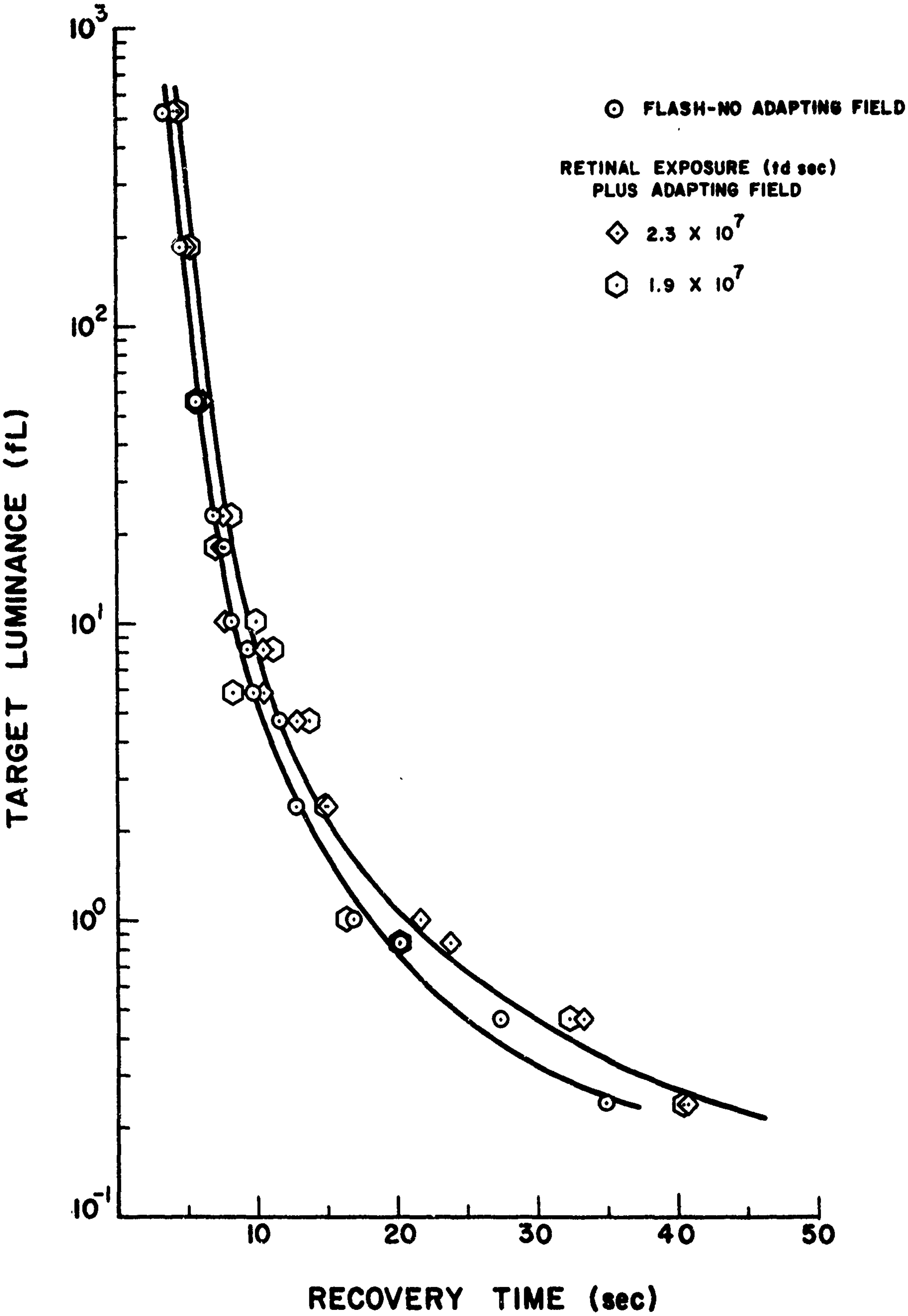

Figure 13. Flashblindness recovery as a function of target luminance following flash exposures as indicated.

identification of the letters was accomplished by looking through the resulting afterimage in the case of the central and off-center flashes, and around the afterimage for the most peripheral flashes. Figure 5 illustrates the location of the afterimage relative to the foveally-fixated target letter for the nine flashes.

The combined results for the four subjects utilized in this experiment are tabulated in Table VII. Figure 14 presents target identification times as a function of target luminance for the central flash, the average of the four off-center flashes, the average of the four peripheral flashes and the "baseline" (no-flash) condition. This latter condition depicts the subject's best possible performance, and reflects response speed limitations of the apparatus and the subject. It also demonstrates the dark adaptation time required to recover from the effects of one target upon the identification of others of lower luminances.

It is apparent that the recovery times for foveally presented targets, although quite rapid following a flash in the periphery, are not unaffected by the flash - that is, they are slower than those to be seen in the baseline curve. Table VII shows that while subjects required an additional 2.1 seconds to identify the first target, this difference had increased to 4.6 seconds, by the seventh target. The results also show that the effects of a bright extra-foveal flash upon

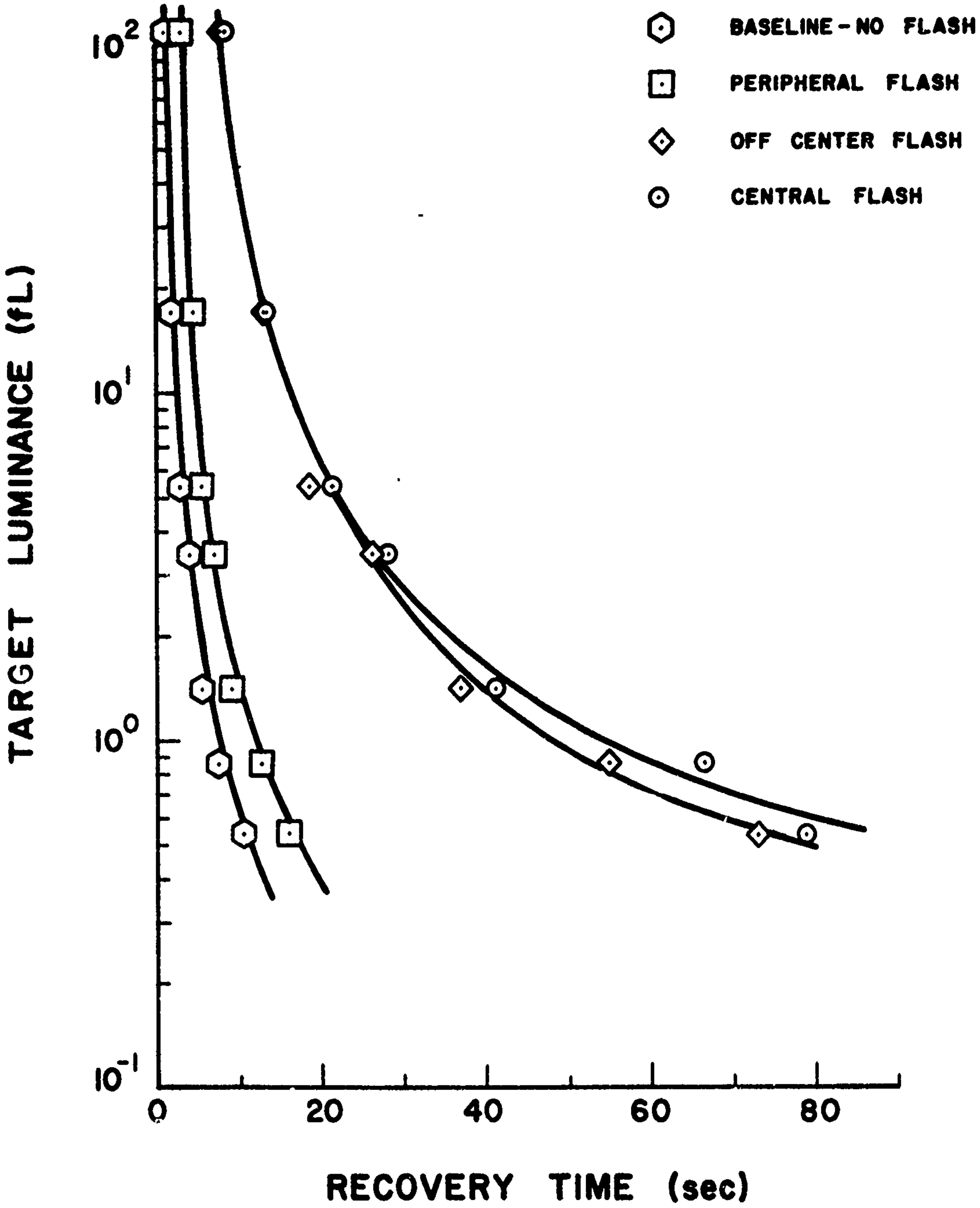

Figure 14. Flashblindness recovery as a function of target luminance and retinal image location. All flashes were of equal intensity and duration.

Table VII.
FOUR SUBJECTS COMBINED
Average Recovery Time in Seconds for 7 Target Luminances and 9 Flash Locations.

Target Luminance (fL)	Baseline	Central Flash	Off-Center Flashes					Peripheral Flashes				
			3 o'clock	6 o'clock	9 o'clock	12 o'clock	$\overline{X}$	3 o'clock	6 o'clock	9 o'clock	12 o'clock	$\overline{X}$
108.0	1.1	8.6	6.9	7.0	8.4	9.9	7.9	3.3	3.2	2.4	4.1	3.2
17.1	2.0	13.7	13.4	12.1	12.8	17.8	13.5	4.9	4.4	3.5	5.4	4.6
5.4	3.1	21.2	20.0	15.8	19.4	21.7	18.8	6.3	5.6	4.4	6.7	5.8
3.4	4.1	28.0	26.2	21.4	27.4	33.7	26.3	7.8	6.9	5.5	8.6	7.2
1.4	5.5	41.2	41.4	31.8	34.6	47.2	37.1	10.8	8.4	7.1	10.1	9.1
0.86	7.5	66.2	62.2	46.3	53.7	65.2	55.0	14.5	13.5	8.7	13.9	12.7
0.54	11.6	79.1	79.2	60.1	78.5	79.6	72.9	17.8	18.3	10.8	17.3	16.2

foveal visibility are more than transient.

3.3.2 Recovery time as a function of flash image size.

A freely viewed flash source was utilized in the study of visual acuity recovery as a function of foveal flash field size. No conventional recovery curves were obtained during this work primarily because of machine limitations. In addition, as the flash field size was changed the subject's mode of identification (through or around the afterimage) changed. A total of eight flash field sizes were investigated between 1^{o} and 4.4^{o} for exposures of 6.5×10^{5} td sec.

The data presented in Table VIII are plotted in Figure 15 along with results from a statistical analysis. The mean, median, range and inter-quartile range are shown for each flash field size. The inter-quartile is the interval containing the central 50% of all the recovery times for each flash field size. The median is less affected by spurious points than is the mean, and tends to better reflect the trend.

A cursory examination of the data of Table VIII is sufficient to indicate a bi-modal distribution of recovery times - particularly for the larger flash fields. This is also born out by the subjects' responses to questions of whether target identification was performed

Table VIII. Visual acuity recovery times (sec) to a 0.4 fL task as a function of flash field size.

SUBJECT	1.0°	1.5°	1.75°	2.0°	2.5°	3.0°	3.8°	4.4°
J.B.	-	-	1.5 A	-	7.5 A	4.0 A	-	26.0 T
W.B.	6.0 A	12.0 A	5.0 A	35.0 T	-	30.0 T	30.0 T	-
	-	-	3.0 A	-	11.8 A	17.0 A	-	19.5 T
B.L.	5.0 A	2.3 A	33.0 T	17.5 U	-	27.5 T	43.0 T	-
	-	-	4.0 T	-	52.0 T	47.5 T	35.1 T	-
R.W.	5.0 A	5.0 A	4.2 A	24.0 T	-	6.5 A	23.8 T	-
	11.0 U	3.0 U	5.0 U	-	-	-	-	-
	20.0 U	1.0 U	4.0 U	3.0 U	-	5.0 U	25.0 U	-
	5.0 A	10.0 A	5.0 A	7.0 A	-	9.0 A	8.0 A	-
J.R.	16.0 A	3.0 A	7.0 A	10.0 A	-	41.0 T	9.0 A	-
	2.2 A	20.4 A	26.2 A	4.0 A	-	6.0 A	38.8 T	-
J.A.	-	-	3.0 T	-	3.5 T	38.0 T	41.0 T	-
	5.0 A	4.0 A	4.0 A	3.0 A	-	42.0 T	-	-
G.S.	4.0 A	4.5 A	2.5 A	38.0 T	-	49.0 T	11.5 T	-
	-	-	7.0 A	-	28.5 A	40.0 T	-	33.0 T
	-	-	-	-	26.0 A	-	-	-
S.D.	2.0 A	-	-	2.0 A	-	25.0 T	16.0 T	-
	-	-	-	-	5.5 A	-	-	10.5 U
	-	-	5.5 A	-	15.0 T	-	-	-
C.A.	-	18.0 T	30.0 T	-	15.0 A	5.5 A	-	8.0 A
	-	7.0 A	23.0 A	-	7.0 A	4.0 A	-	32.0 T
Around (A)*	82%	75%	67%	50%	70%	41%	18%	16.7%
Through (T)	-	8.3%	22%	30%	30%	53%	73%	66.6%
Uncertain (U)	18%	16.7%	11%	20%	-	6%	9%	16.7%

*Refers to the appearance of the test stimulus relative to the afterimage

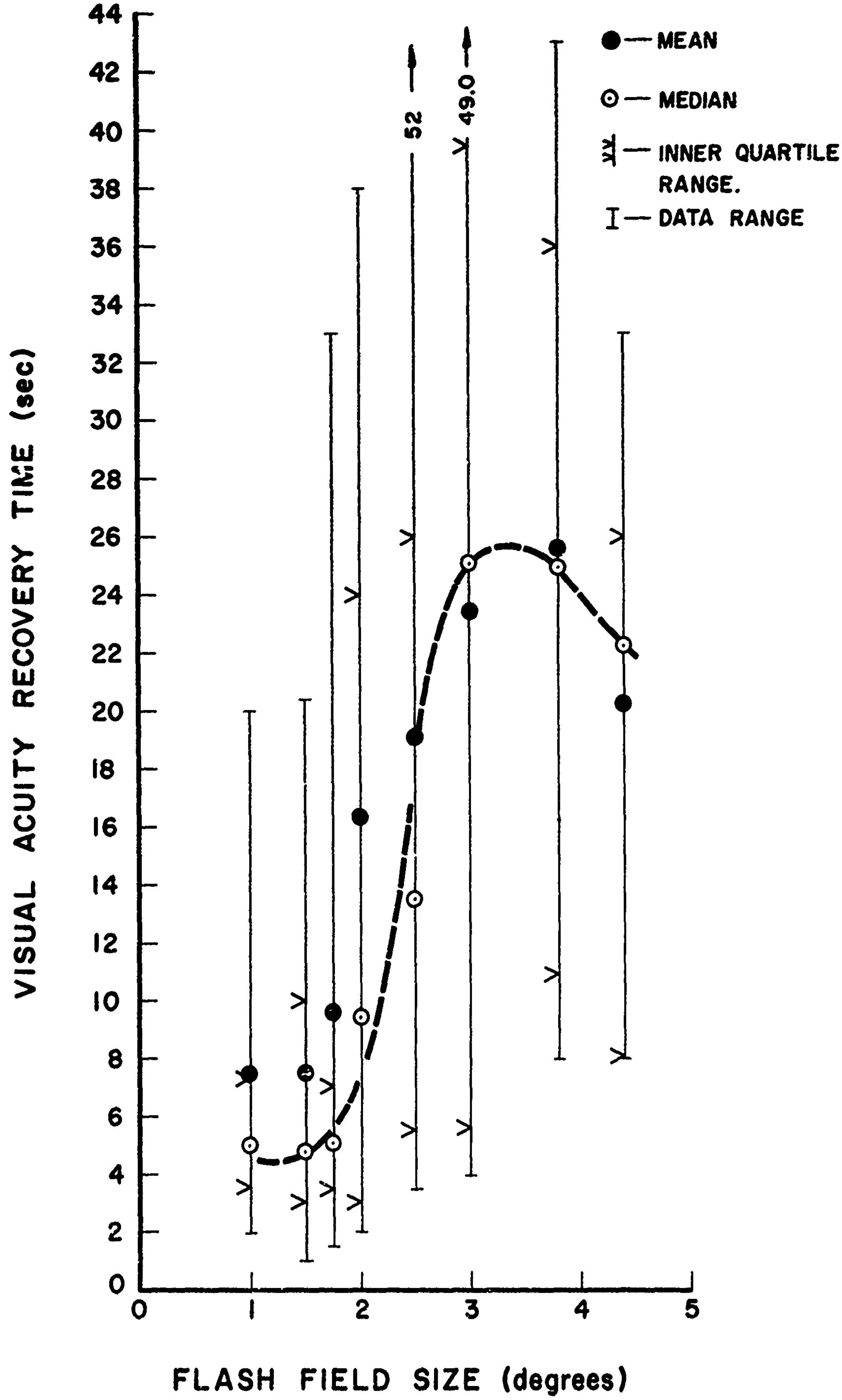

Figure 15. Visual acuity recovery times across subjects as a function of flash field size.

by looking through or around the afterimage of the flash source.

It appears that for all but the smallest flash field size investigated, some data represent detection with central target fixation, i.e., looking through the decaying afterimage, while other data reflect extra-foveal fixation - looking around the afterimage. The results imply that recovery from the smaller flash field was most rapid when the subject looked around the afterimage. However, as the flash field approached 3° in subtense, it appears that average visual acuity recovery was significantly slowed, perhaps due to a greater tendency to use foveal fixation in attempting to look through the afterimage. The recovery time range significantly increases as the mean and median recovery times increase. It is likely that the subjects executed searching fixation movements, consciously or unconsciously, in an effort to resolve the target foveally. On the other hand, certain subjects demonstrated the ability to suppress such a tendency and to achieve resolution of the 20/40 Snellen letter outside the flash-blinded area.

Additional work with flash field size extended the maximum to 5° and resulted in the curves shown in Figure 16. This figure shows that task identifications for detail of 20/40 size will tend to be made with equal frequency by either mode of identification (looking through or around the afterimage) when the subject is presented with a

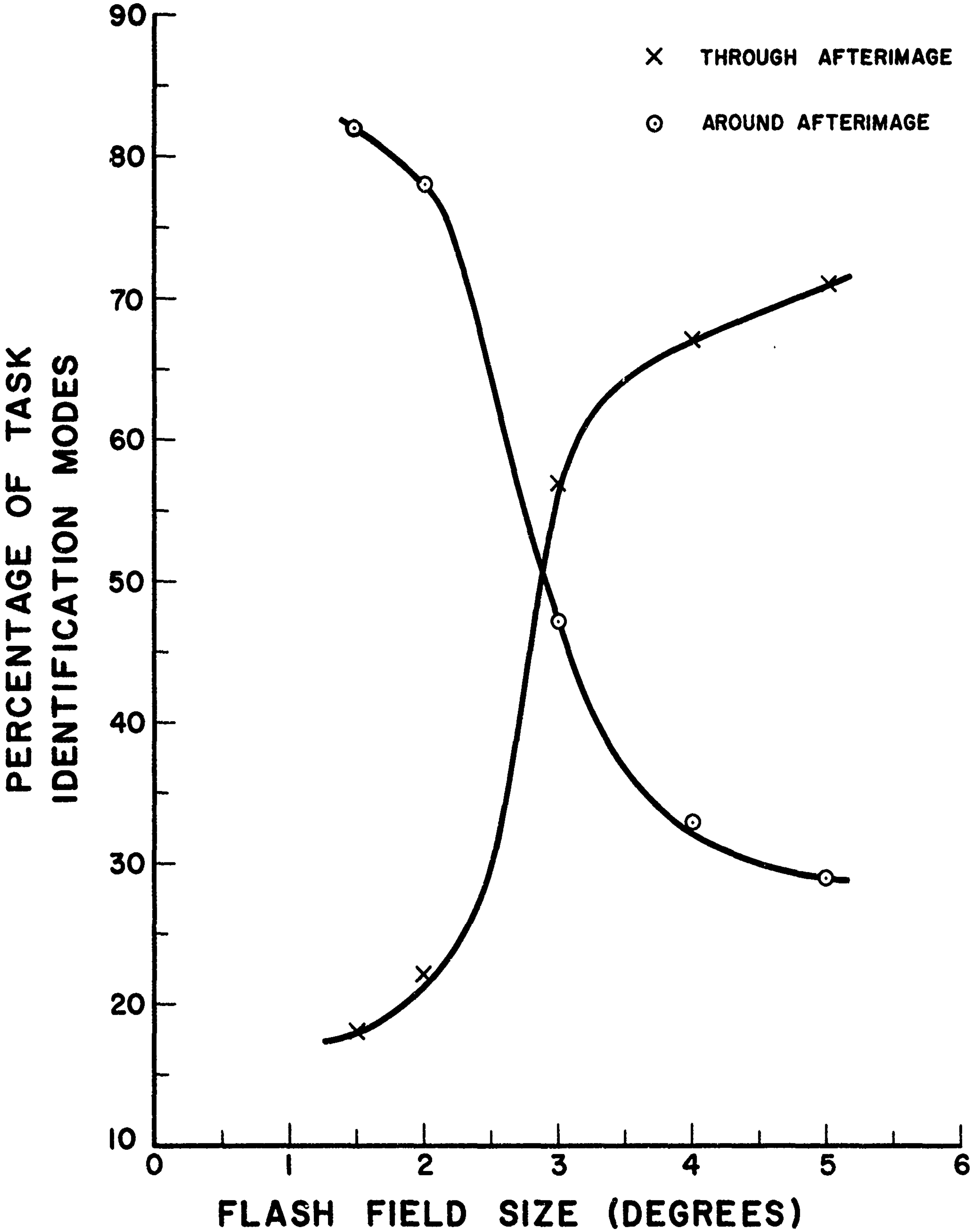

Figure 16. Percentage of task identification modes averaged across three subjects for a target of 0.4 fL luminance.

foveally fixated flash of 2.75° to 3.0° angular subtense.

In the work described above, the retinal illuminance remained identical for all experiments. Therefore, the changes in visual acuity recovery time are not a function of flash luminance but of flash image size. As this flash size increased - while holding illuminance equal - a size should be reached where the recovery times do not increase. Figure 15 indicates in fact, that the recovery times tend to decline between flash field sizes of 4° to 5°. However, it is not likely that this tendency is significant.

3.4 Intensity x Time Relationships

This series of experiments was designed to investigate the time-intensity relationships of equal energy flashes delivered to the dark adapted retina. A total of five related experiments were conducted. Three experiments were designed to deliver the same total flash energy within each experiment and two experiments were designed to produce equal photopigment bleach.

3.4.1 Equal energy exposures

The first of three sets of flash exposures (3.9×10^6 td-sec) employed durations of 0.5 msec 0.82 msec and 1.5 msec. The upper portion of Figure 17 shows mean recovery times to these pulses when averaged across three subjects.

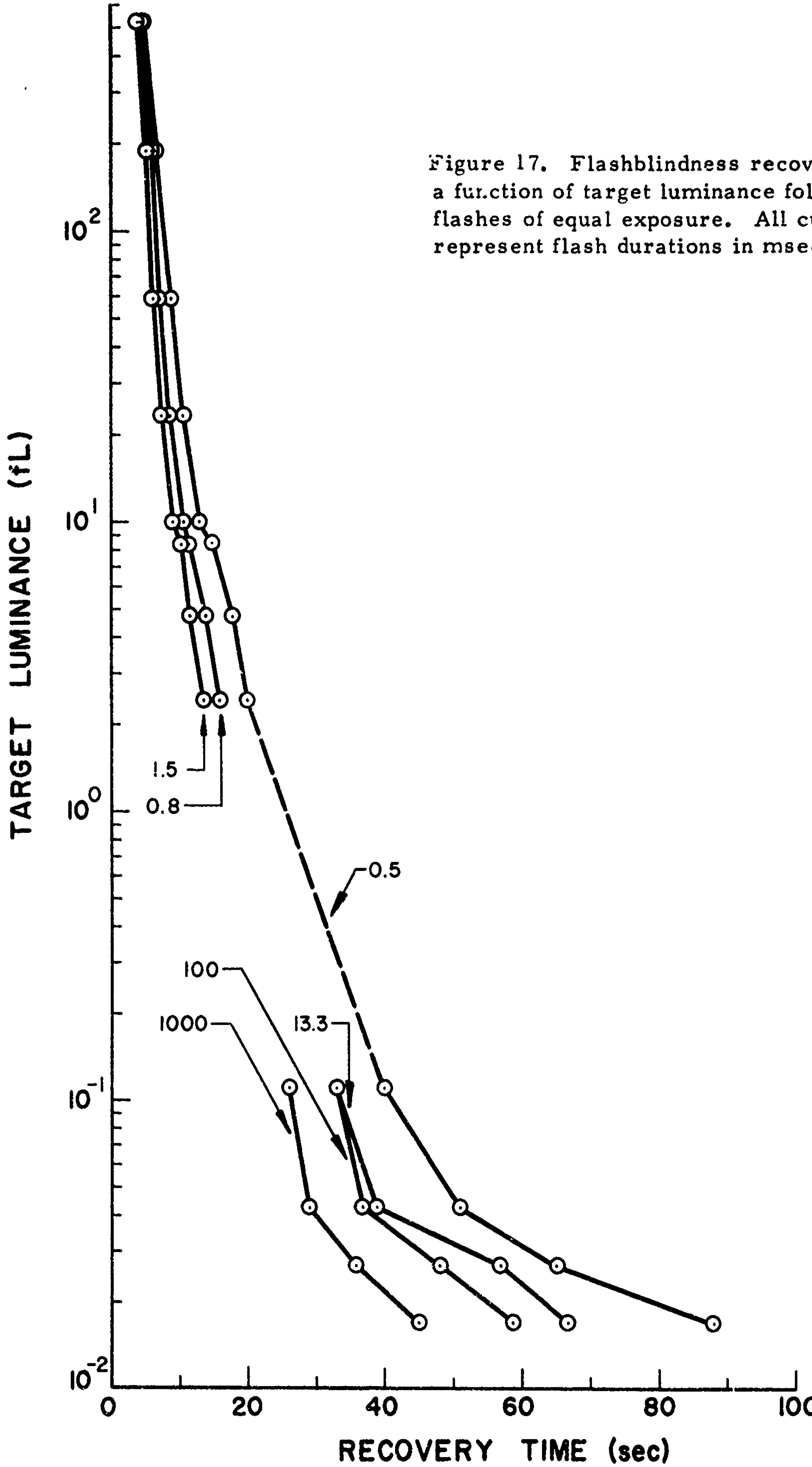

Figure 17. Flashblindness recovery as a function of target luminance following flashes of equal exposure. All curves represent flash durations in msec.

The second experiment utilized flash pulses of 0.5 msec, 13.3 msec, 100 msec, and 1000 msec, all with a retinal exposure of 3.9×10^6 td-sec. Recovery from these flash durations, averaged across subjects, is shown in the lower portion of Figure 17. The dashed line connecting the two groups of data represents a possible continuation of the recovery curve for the 0.5 msec flash pulse. In both the upper and lower sets of data the fastest pulse (0.5 msec) resulted in the longest recovery times. Also in both cases an ordered succession from the slowest to the fastest pulse was evident.

Even though the pulses were of equal energy, results of the flash exposures were not the same. These data indicate that flash-blindness recovery is directly related to flash intensity and inversly related to pulse duration provided retinal exposure is held constant.

3.4.2 Equal bleach exposures

Recovery times for brief flashes were compared with recovery times for extended exposures that were equated for (a) total concentration of intact cone photopigment following exposure, or (b) concentration of photoproduct C. Photoproduct C has been used to characterize the increase in visual sensitivity following flashblindness.[2]

The experiment involved a comparison between a total of three

exposure-histories: two 40 msec flashes at 1.8×10^6 td and 9.2×10^7 td, respectively, and one 100 sec exposure at 9.4×10^4 td. The intensities needed to produce the desired concentration of intact photopigment and photoproduct C were calculated using the generalized five-component model of photopigment kinetics.(2) The intensities, durations and pertinent photochemical effects of the three exposure-histories are summarized in Table IX (first three entries).

Figure 18 presents recovery times, averaged across three subjects, as a function of target intensity. For approximately the first 15 seconds, recovery following a brief flash is slower than recovery from a 100 second exposure: this relationship is reversed in the later stages of dark adaptation, with the flash permitting recovery to the dimmest target almost a minute sooner than that permitted by the extended bleach. Recovery is very rapid following the dim flash, which was equated with the extended exposure on the basis of photoproduct C. It was only for identification of the brightest target in the series that the flash permited a recovery time equal to that permitted by the extended exposure.

3.5 Foveal Dark Adaptation with Acute and Gross Targets

The time course of foveal dark adaptation depends upon the exposure history of the eye and the criteria by which adaptation is determined.

Table IX. Summary of experimental conditions for equal bleach experiment.

Duration	Intensity (td)	Relative Concentration of Intact Photopigment	Concentration of C
40 msec	1.8×10^6	0.97	0.023
40 msec	9.2×10^7	0.30	0.68
100 sec	9.4×10^4	0.30	0.023
120 sec	3.5×10^4	0.48	--

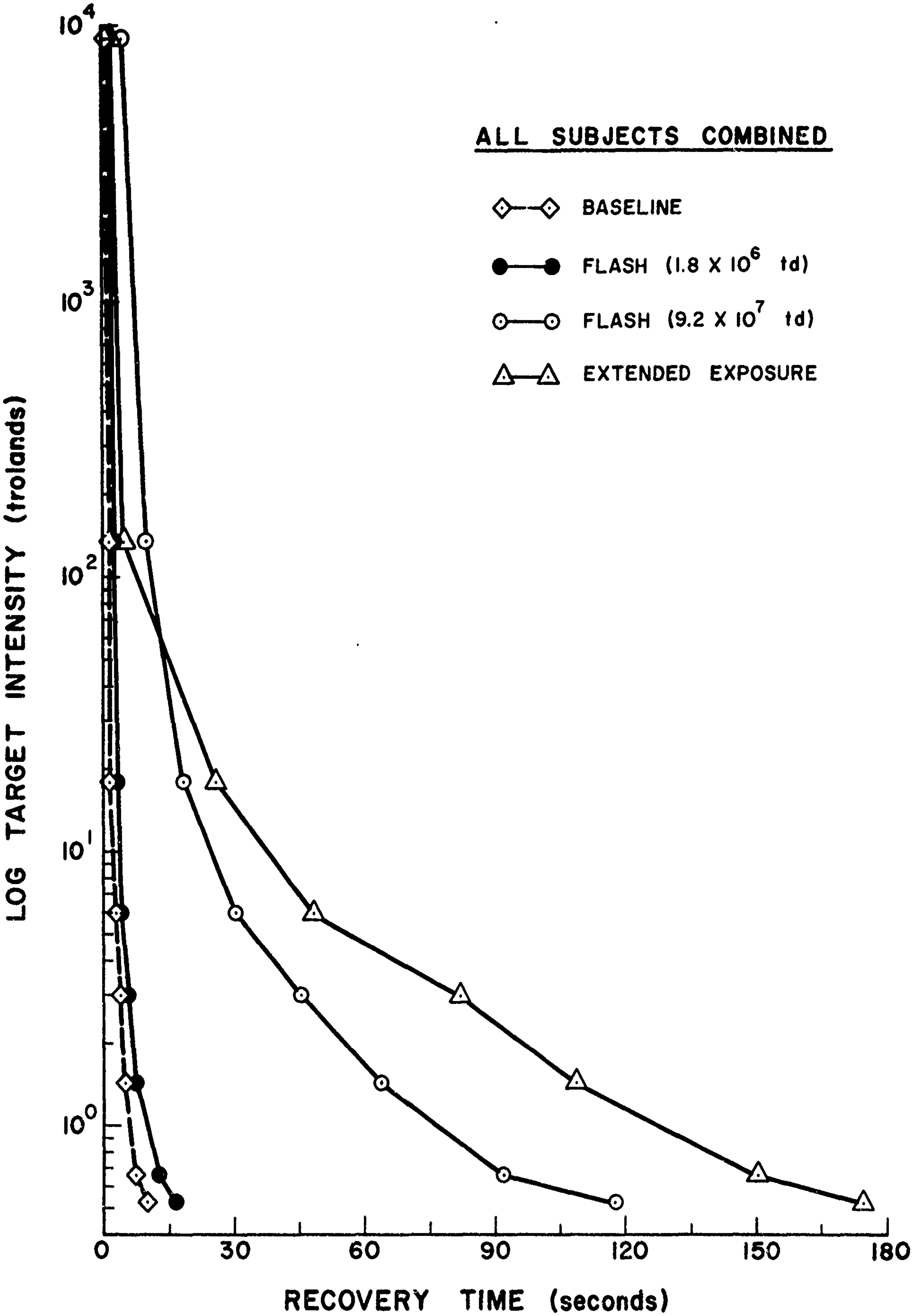

Figure 18. Flashblindness recovery as a function of target retinal illuminance following flash exposures as indicated.

Any experiment is which the fovea is light adapted and subsequently allowed to dark adapt will have, in the dark adaptation phase. some artifact component. This will be due to the task luminance which will maintain the fovea in a slightly light adapted state. In lieu of these facts. the following data are presented as representative of foveal dark adaptation.

3.5.1 Foveal dark adaptation following short flash exposures

Virtually any experiment in which the subject is required to perform a visual task after the flash can be used to extract data on foveal dark adaptation. The experiments illustrated in Figure 19 were chosen because of the number of data points available. No effort was made to choose only those experiments with similar initial bleach values. Figure 19 illustrates the fact that the human recovery response is very similar under a variety of flash and target conditions. These conditions are listed in Table X and reference the curves in Figure 19.

3.5.2 Foveal dark adaptation following extended retinal exposures

A second series of experiments was conducted in which the subject was light adapted for 100 and 120 seconds. Photopigment concentrations are given in Table IX. Curves illustrating dark adaptation following these exposures are shown in Figure 20 and are clearly

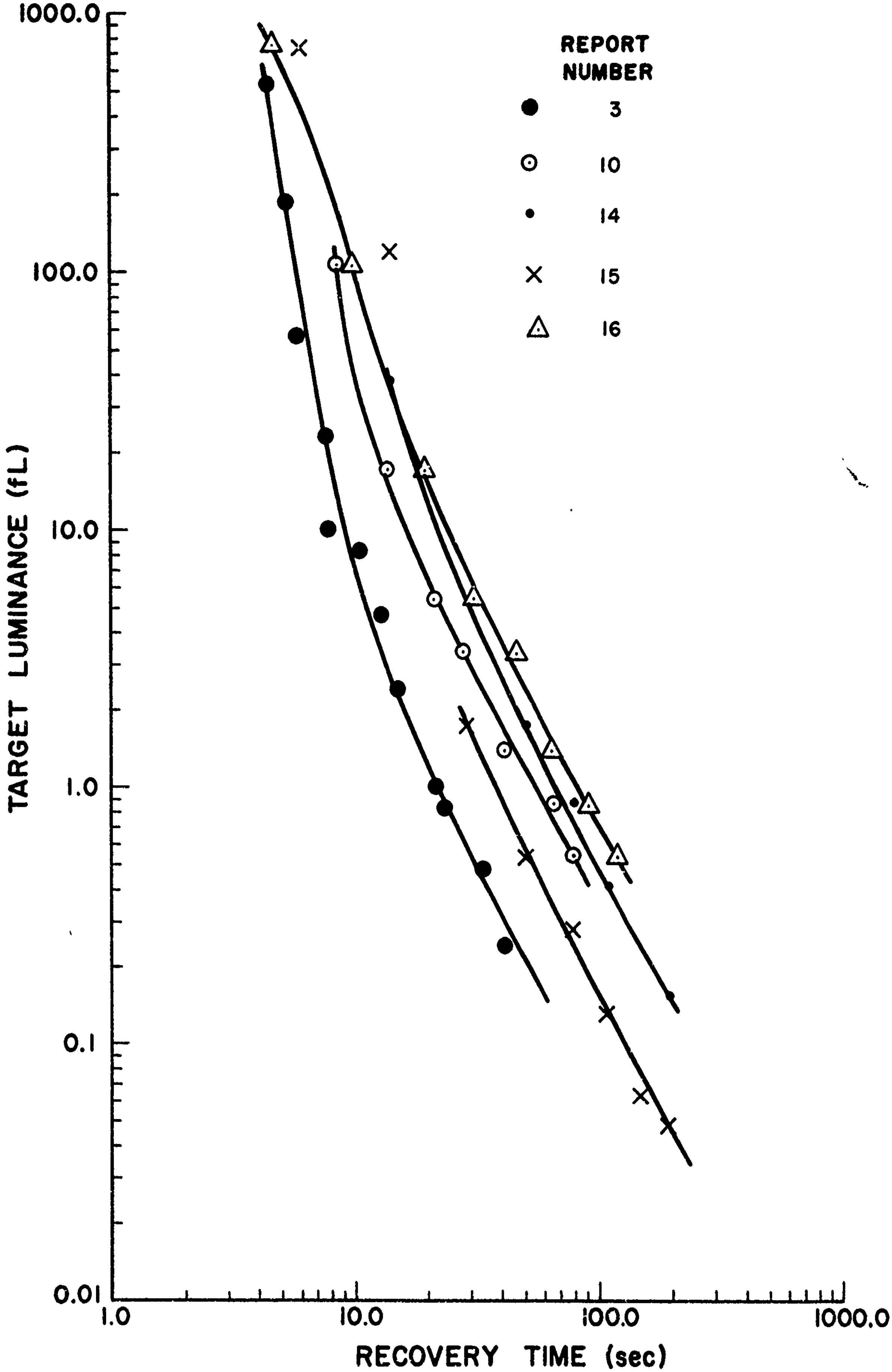

Figure 19. Foveal flashblindness recovery as a function of target luminance following short flash exposures.

Table X. Experiments and parameters utilized for the study of foveal dark adaptation following short flashes.

Report Number	Retinal Illuminance (td)	Flash Duration (msec)	Recovery Target
3	2.1×10^{10}	0.8	grating
10	1.14×10^{10}	0.5	letters
14	1.0×10^{9}	1.5	letters
15	1.0×10^{9}	1.5	line
16	9.2×10^{7}	40.0	line

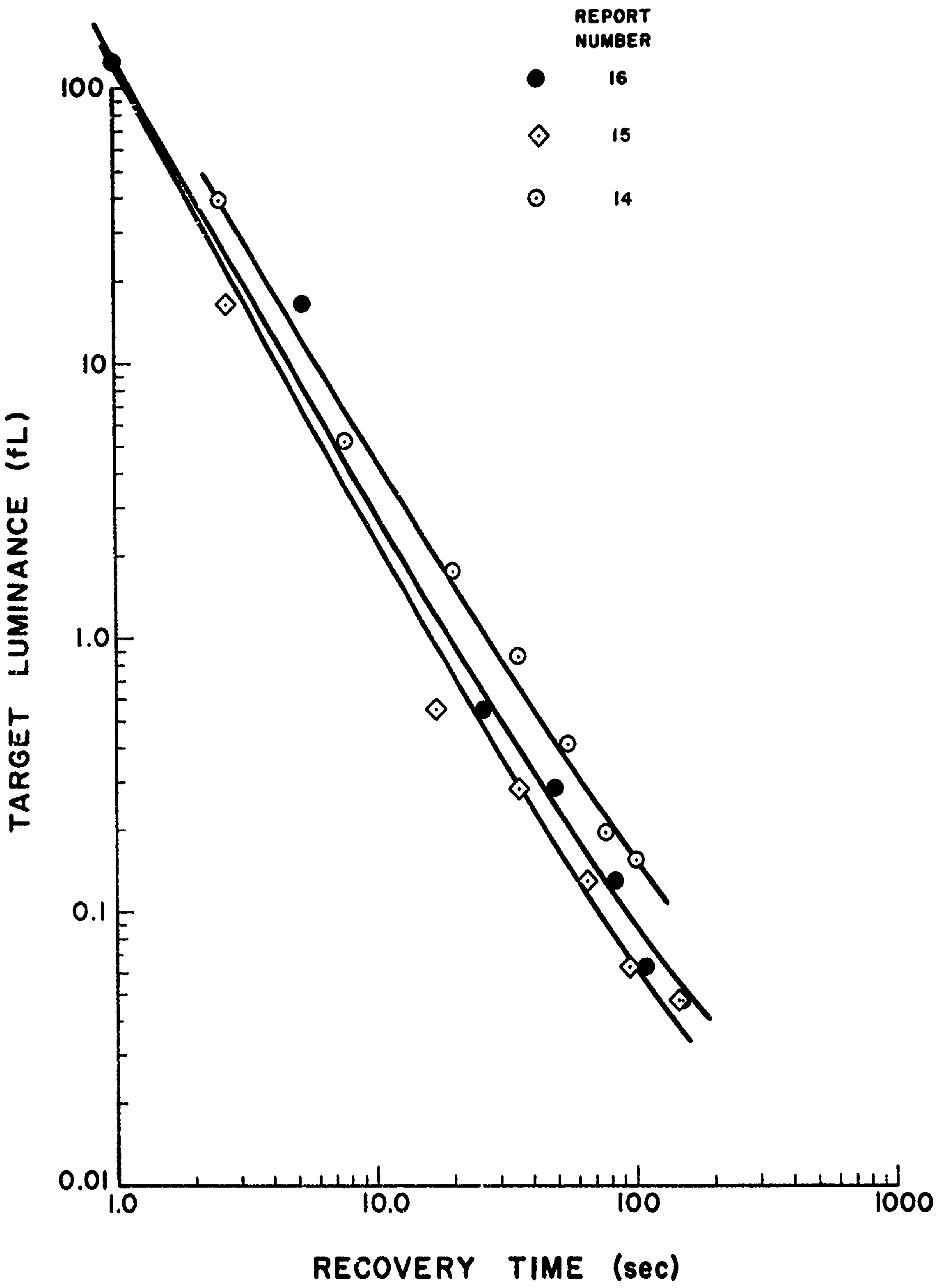

Figure 20. Foveal recovery as a function of target luminance following extended retinal exposures.

different from the short flash recovery. Dark adaptation after different bleaching intensities and times are seldom identical even though attempts might be made to control the effect by maintaining an equal time-intensity product. Due to this fact it is often difficult to compare different recovery effects.

3.6 Variability of Interindividual Flashblindness Recovery Times

The study of variability was accomplished in two phases. Phase one consisted of a study to determine the intersubject variability of three subjects through one experiment. Also studied in phase one, was the variability across relatively few subjects and three experiments for an entire flash blindness recovery curve. Phase two consisted of an experiment designed to study intersubject variability as determined by recovery to a single fixed luminance target.

3.6.1 Intersubject variability for a complete flashblindness recovery curve.

A brief study of small sample variability through one experiment was necessary before any attempts were made to s'udy relatively large population samples. Typical intersubject variabilities for one experiment are shown in Figure 21 for three subjects. The results of a second approach to intersubject variabilities are shown in Figure 22. The latter figure shows the standard deviations about the mean recovery times for five subjects and three experiments.

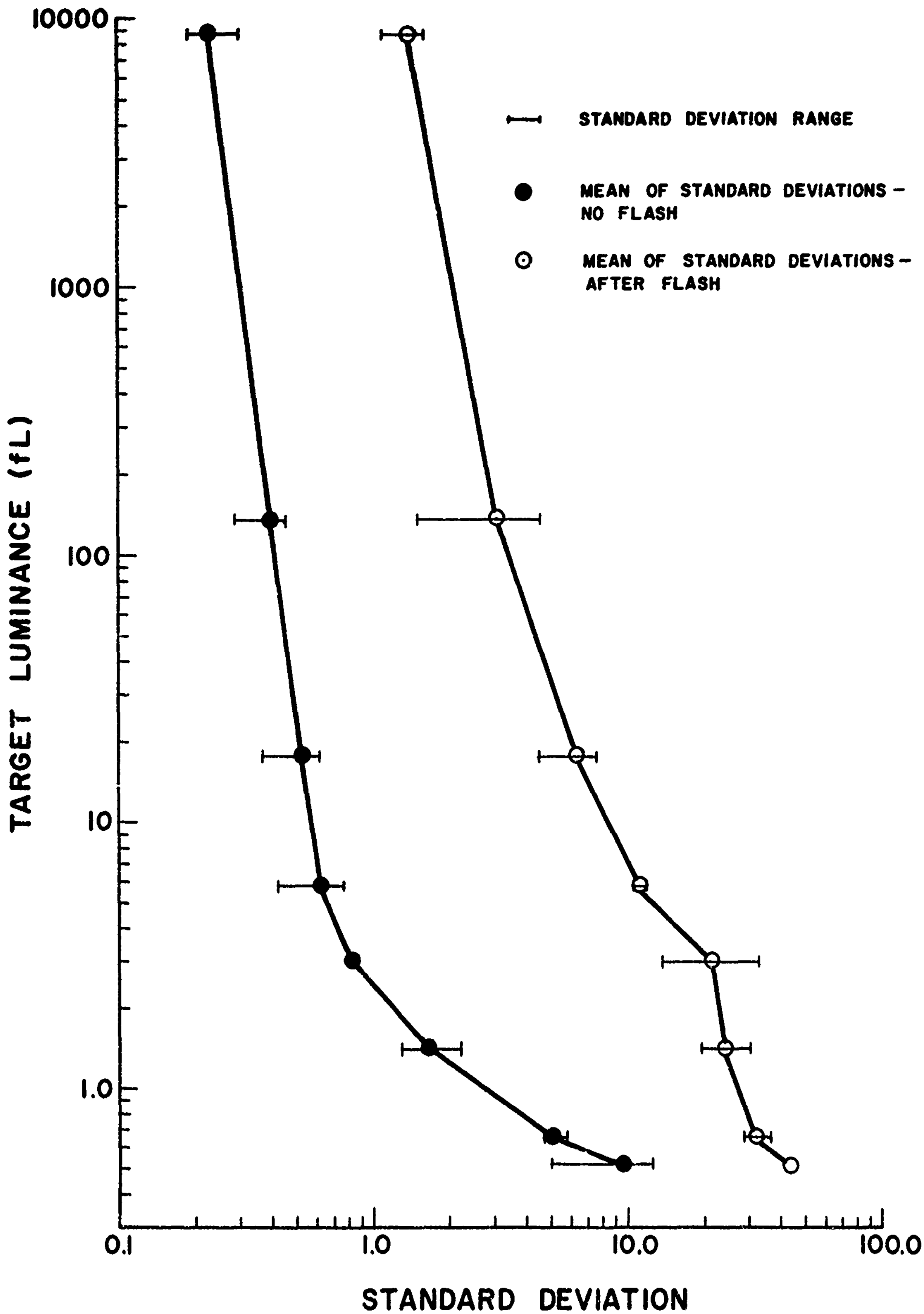

Figure 21. Standard deviations about the mean flashblindness recovery time across three subjects for one experiment.

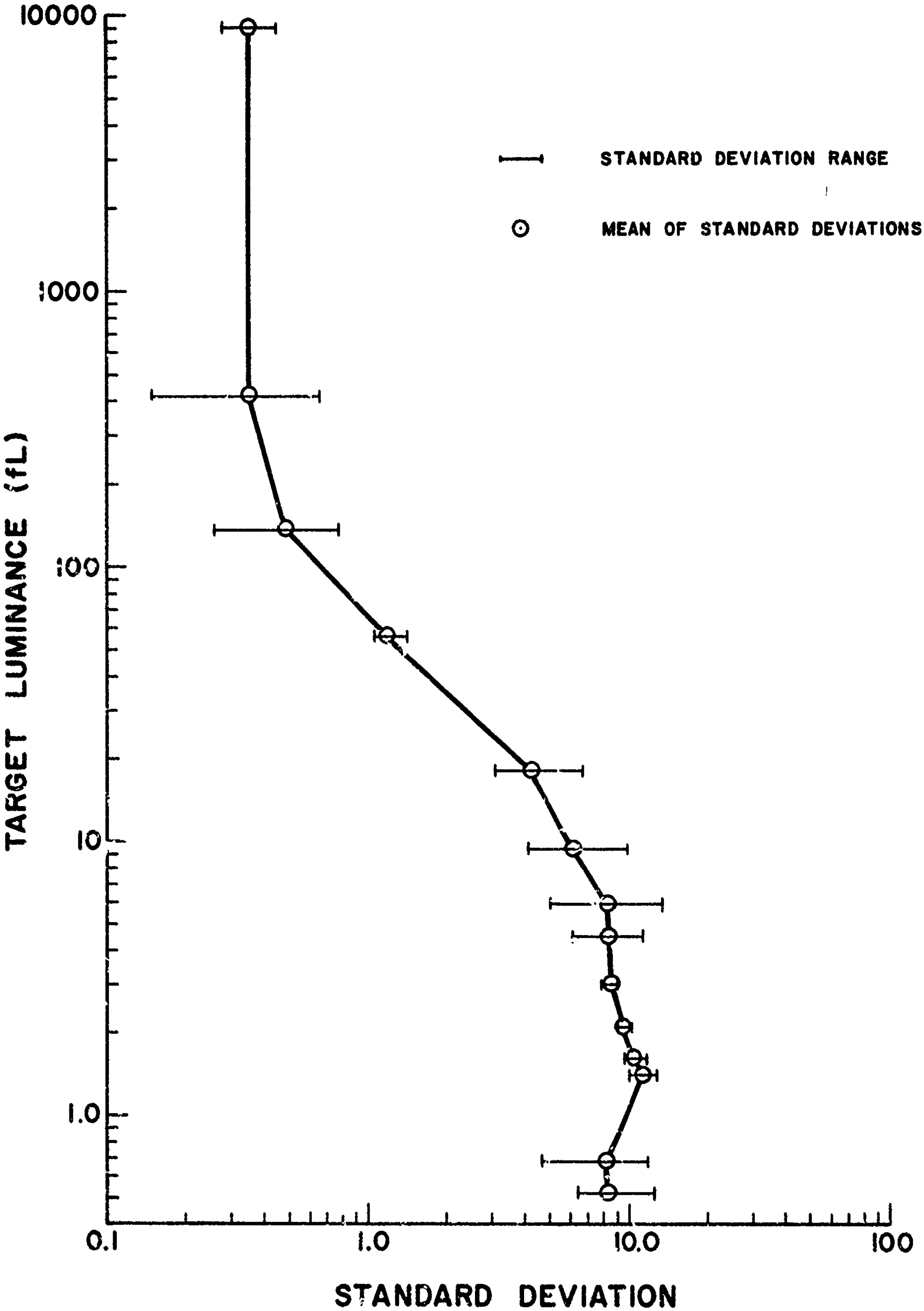

Figure 22. Standard deviations about the mean flashblindness recovery times across five subjects and three experiments.

3.6.2 Intersubject variability to a single fixed luminance target

Ten subjects were exposed to flashes of identical luminance but various angular subtense and to different letter recovery targets of the same luminance. A total of 161 single tests were conducted with flash fields subtending 1° to 5° at the eye. The responses were divided into ten second classes and presented as percent of responses in each class (Figure 23). A further examination of the data revealed a bimodal response of displacing the afterimage to one side in order to identify the letter or looking directly through the afterimage to make the identification. Figure 24 shows the percent distribution for each of these modes of identification. The biomodal distribution of the "around" data is deceptive in that if smaller classes are chosen a more normal distribution is approached (Figure 25).

3.7 The Effect of Flash Source Intensity and Duration on Recovery Times, Afterimage Brightness and Ratio of Photopigment Bleached

The results of these related topics will be presented below as three experiments.

3.7.1 The effect of flash source intensity and duration on recovery times.

Basically, the entire program of flashblindness research was an

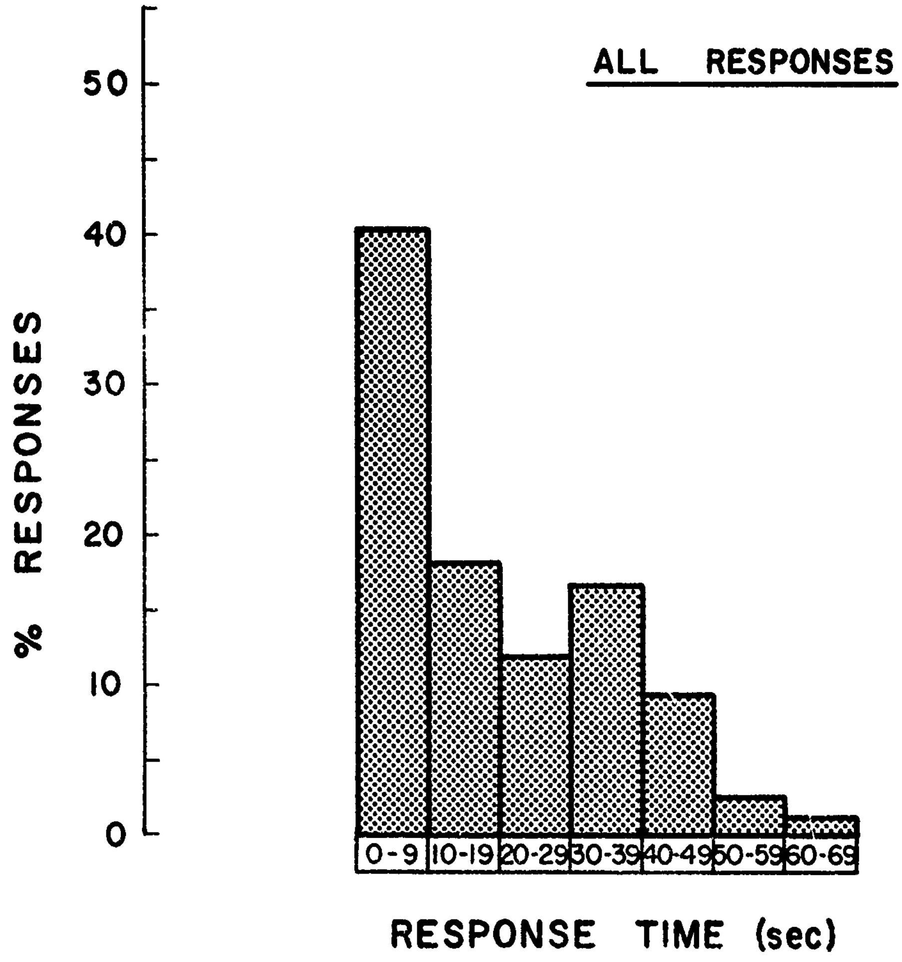

Figure 23. Percent total responses as a function of time following different size flashes of a single luminance level.

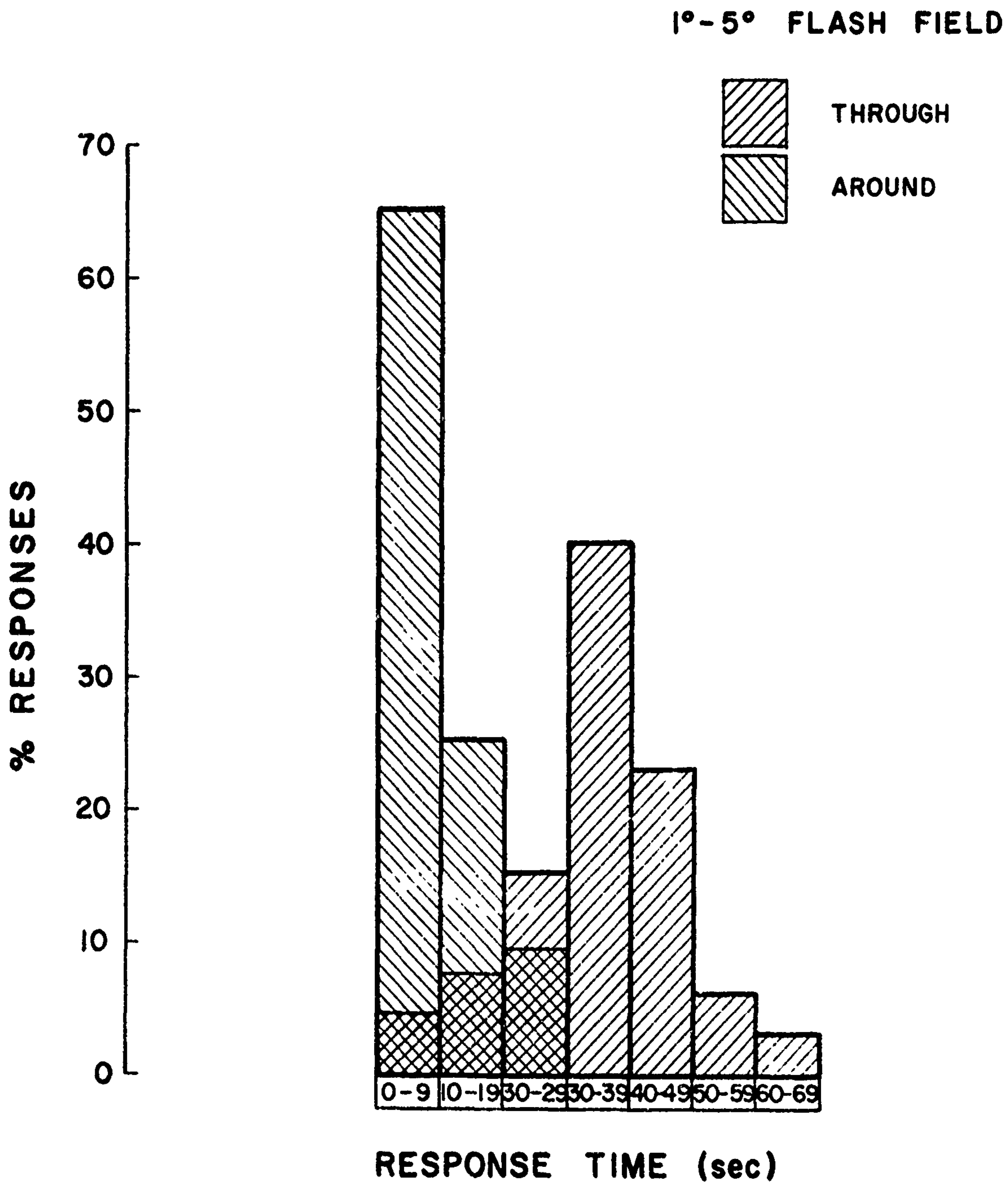

Figure 24. Percent responses around or through centrally fixated afterimages.

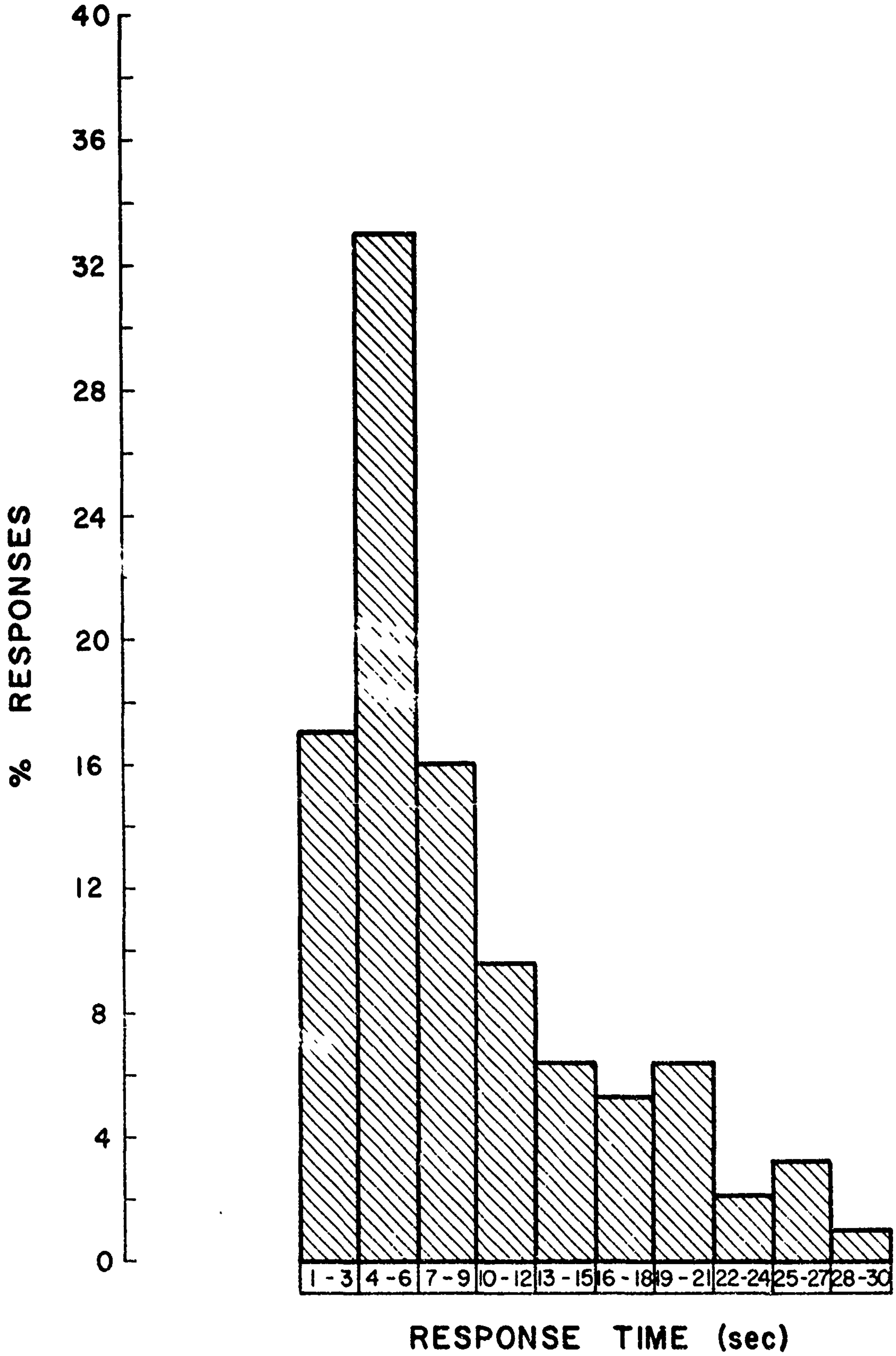

Figure 25. Percent responses around centrally fixated afterimages.

attempt to define this effect. Flashblindness recovery is dependent upon both intensity and duration, therefore, any data presented in graphical form should be represented in three dimensions which is, of course, impossible on paper.

3.7.1.1 Reciprocity

This work was designed to present to the subjects, flashes of equal energy at four different intensities and durations. The results across three subjects are shown in Figure 26. If reciprocity had held, all four points of each task luminance value should have been on a straight horizontal line. This is clearly not the case and demonstrates that even with manipulation of flash intensity and duration, identical recovery effects are not likely. Reciprocity has also been discussed in Section 3.4.1.

3.7.1.2 Flashes of equal duration

Three sets of data were obtained which show recovery times as a function of retinal illuminance while holding flash duration constant. Figure 27 shows the increase in recovery time caused by a factor of ten increase in flash intensity.

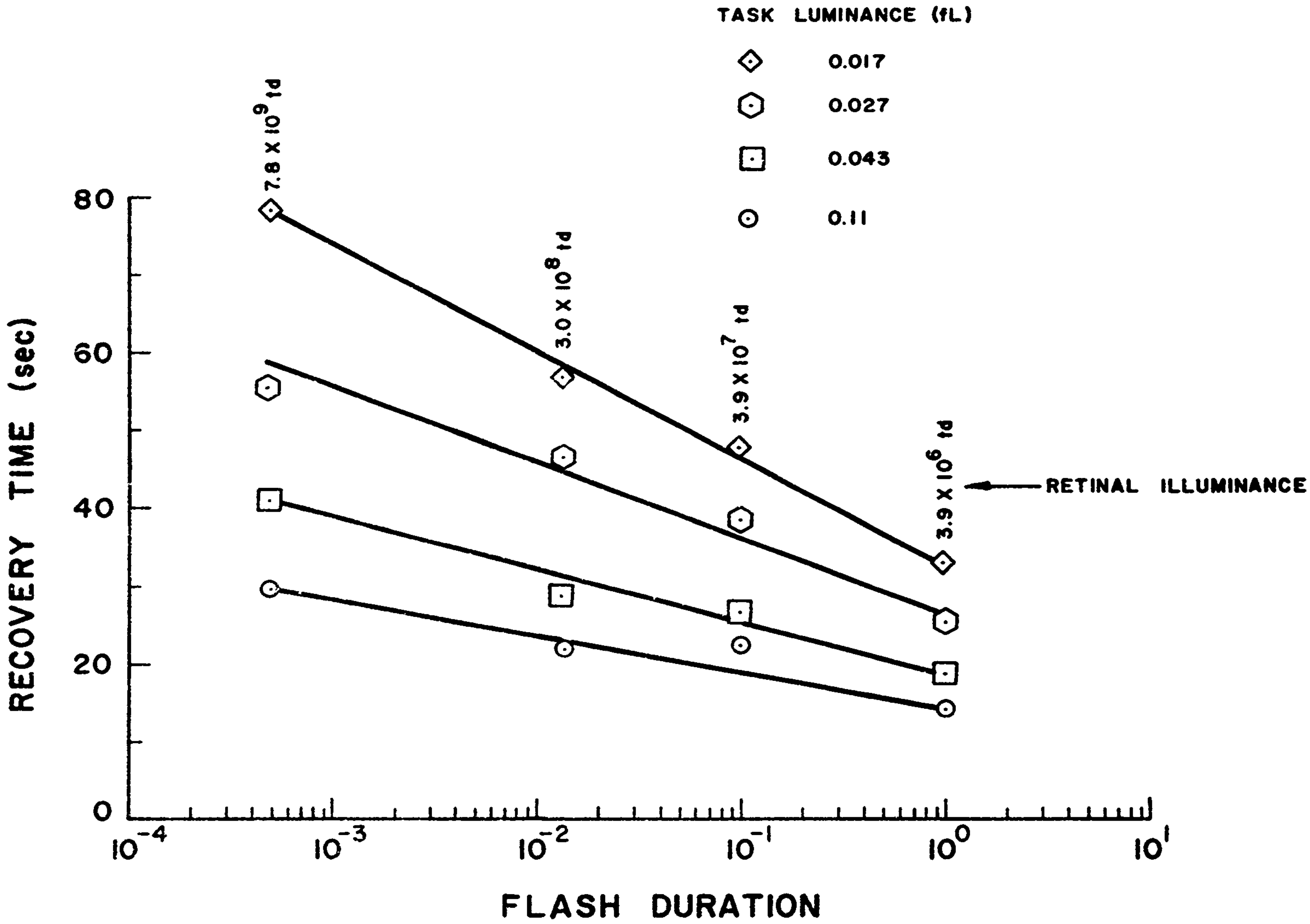

Figure 26. Flashblindness recovery as a function of flash duration and retinal illuminance.

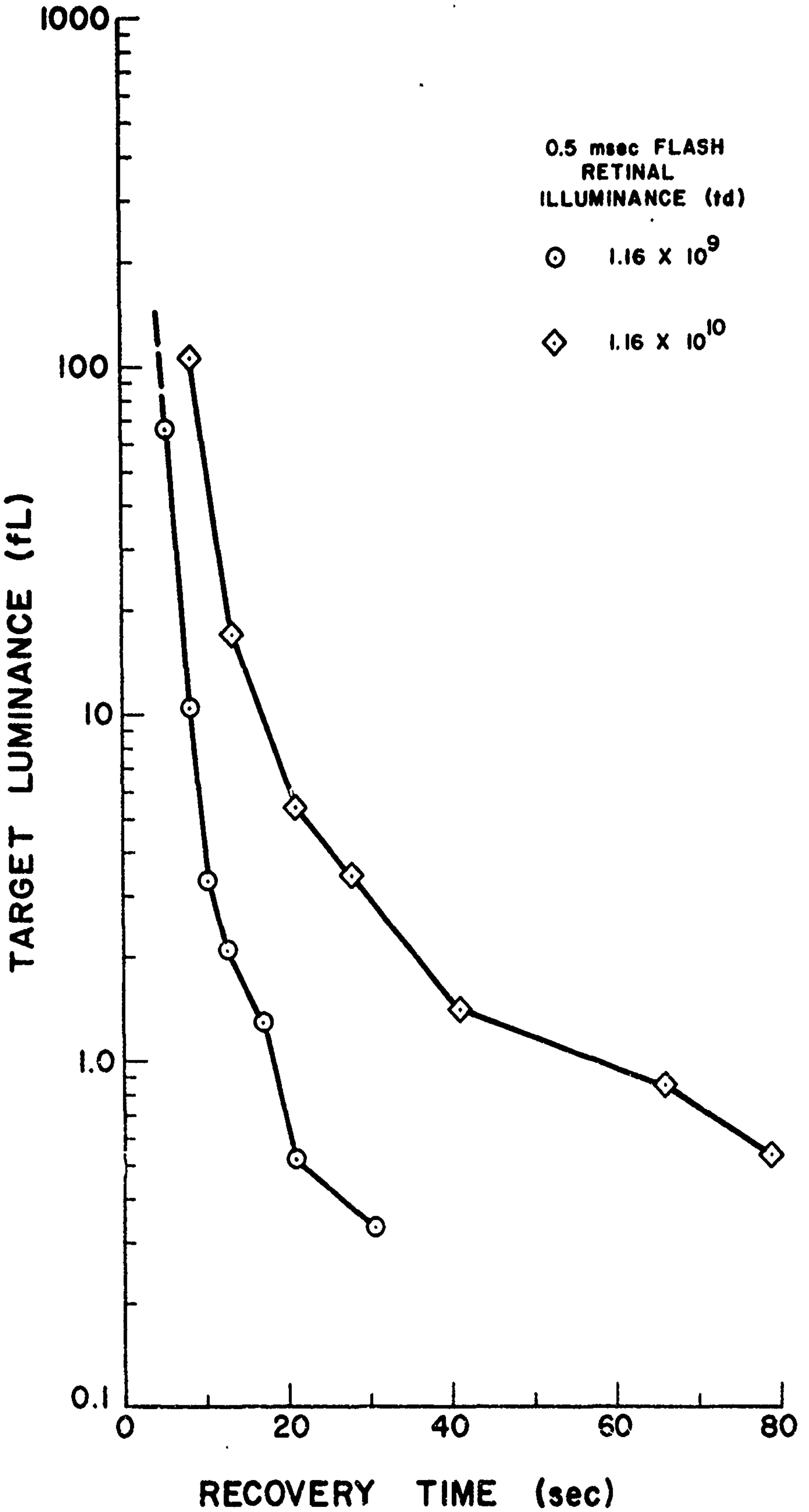

Figure 27. Flashblindness recovery following flashes of intensity and duration as indicated.

Flash intensity increase factors of 1.6 and 10 over the lowest flash intensity are presented in Figure 28. A maximum intensity increase factor of 51 is shown in Figure 29.

If the flash values of Figure 27 and 29 are considered on the basis of exposure (td-sec), a logical progression from the lowest exposure to the highest exposure is noted. If the curves of Figure 28 are replotted to the scale of Figure 27 and 29, it will be seen that all of Figure 28 lies very close to the 1.8×10^6 td (7.2×10^4 td-sec) curve of Figure 29. If the previous statement alluding to the ordered progression of the exposure curves in Figure 27 and 29 is correct, then the curves in Figure 28 are not correct. Two explanations are possible. The retinal exposure values for Figure 28 may actually be in the range of 10^4 rather than 10^5 and 10^6 or the task luminance values reported for Figure 28 may be too low by a factor of ten.

3.7.1.3 Flashes of approximately equal intensity

A wide range of flash intensities was studied throughout this program. To summarize the results, it was decided to group the flashes into three sets as indicated

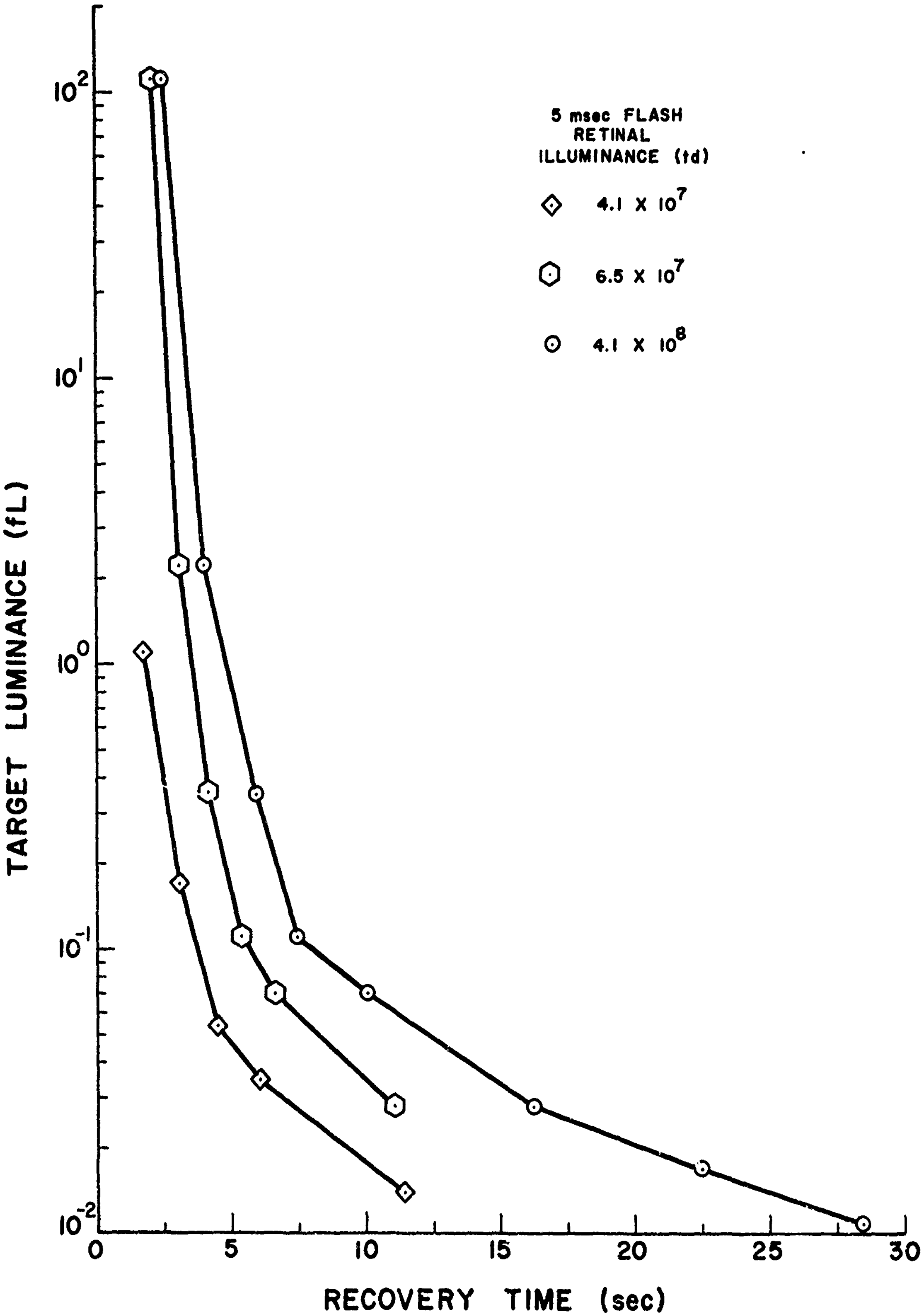

Figure 28. Flashblindness recovery following flashes of intensity and duration as indicated.

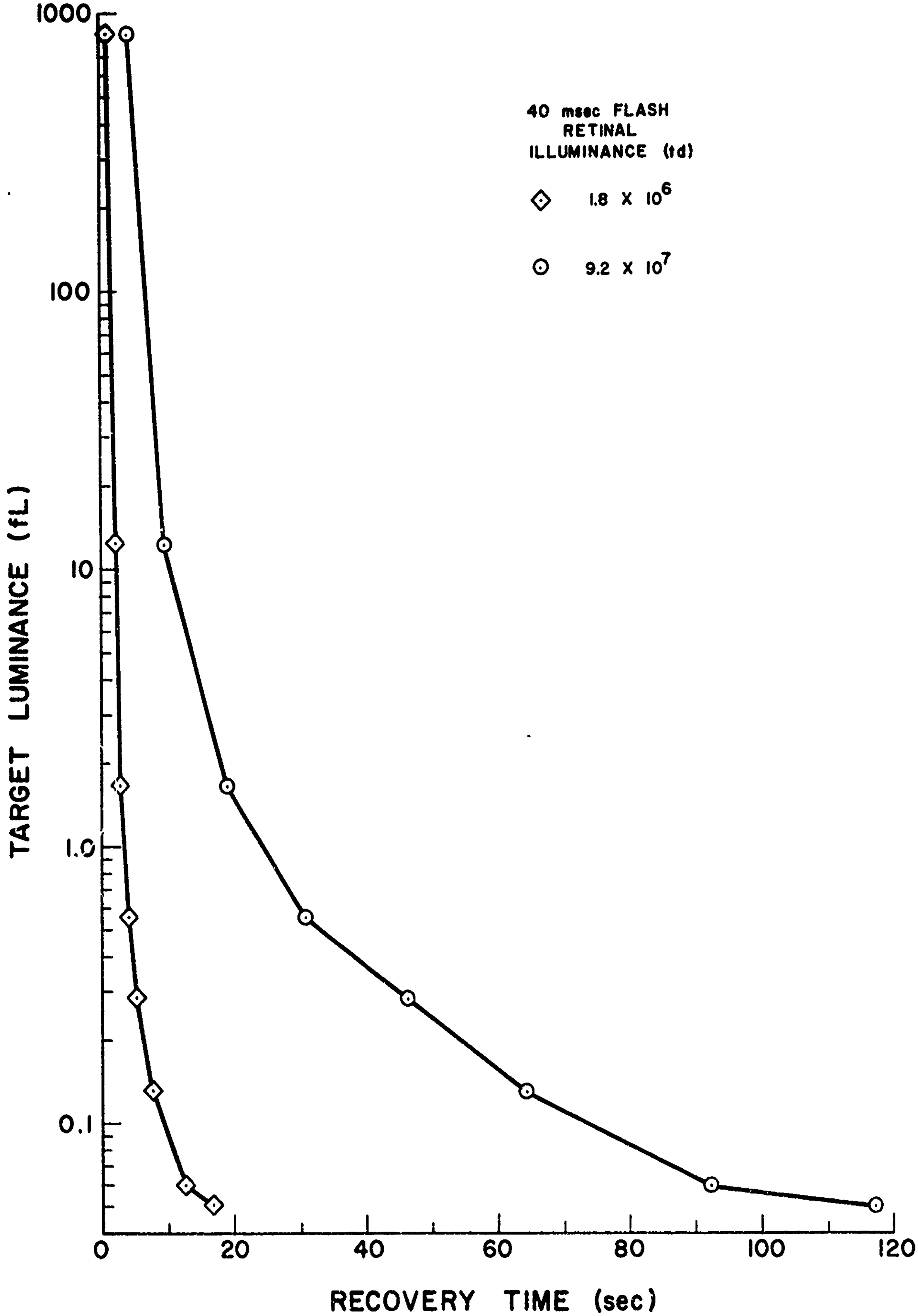

Figure 29. Flashblindness recovery following flashes of intensity and duration as indicated.

by Figure 30, 31 and 32. Although the intensities are not identical, the curves in each figure progress from very short flash durations to longer durations except for two curves in Figure 30. These two curves (40 msec and 100 msec) represent almost identical retinal exposures while the exposures represented by the other curves and figures differ substantially It was shown earlier (Figure 17) that flashblindness recovery is inversly related to the flash duration provided retinal retinal exposure remains constant. This principle is illustrated once again in Figure 30.

3.7.2 <u>The effect of flash source intensity and duration on afterimage brightness</u>

Due to the complexity of judging the brightness of adjacent hereochromatic images, it was not possible to test all subjects under all experimental conditions. The completed procedures consisted of monocular and binocular matches with two match sets attempted on a flash which had been dimmed by a factor of ten. Figure 33 shows the array of data points gathered on the monocular matches. Results of the binocular matches are shown in Figure 34 and generally show slightly lower luminance and time values than do the monocular matches.

The flash was reduced by a factor of ten and several monocular matches attempted by subject CW (Figure 35). This curve is virtually identical to the match by CW shown in Figure 36. It should be pointed out that the monocular match by CW (Figure 36)

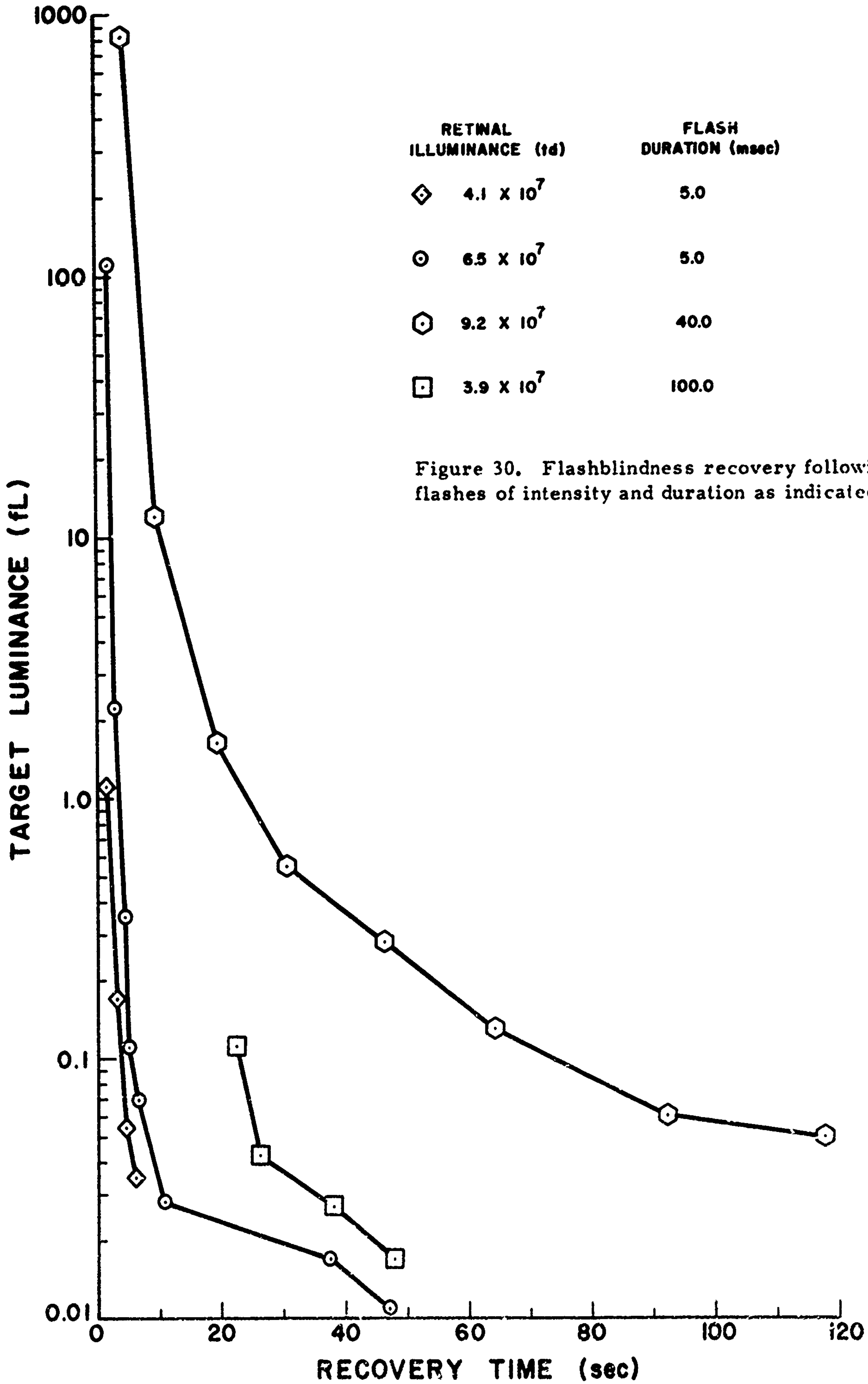

Figure 30. Flashblindness recovery following flashes of intensity and duration as indicated.

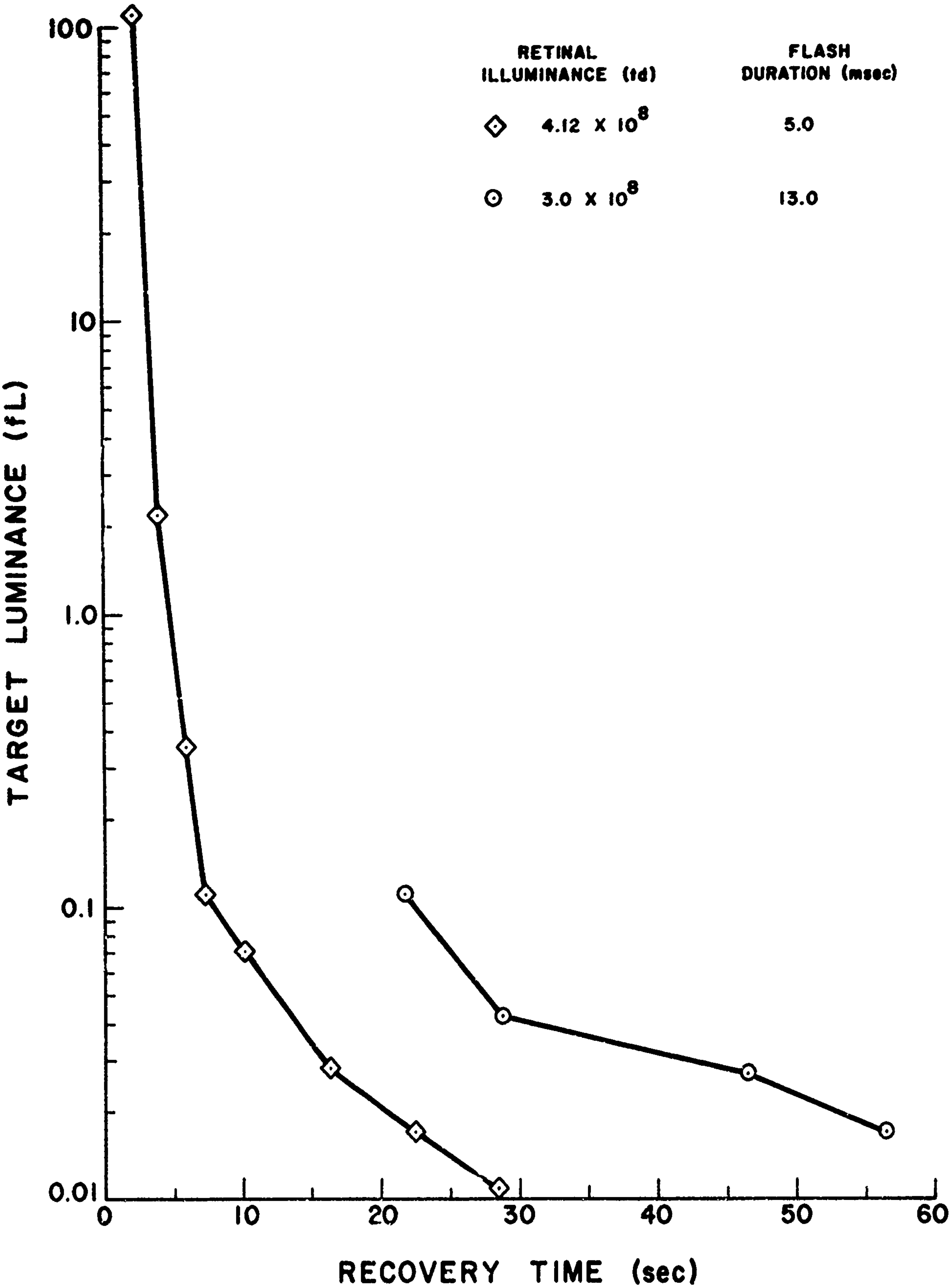

Figure 31. Flashblindness recovery following flashes of intensity and duration as indicated.

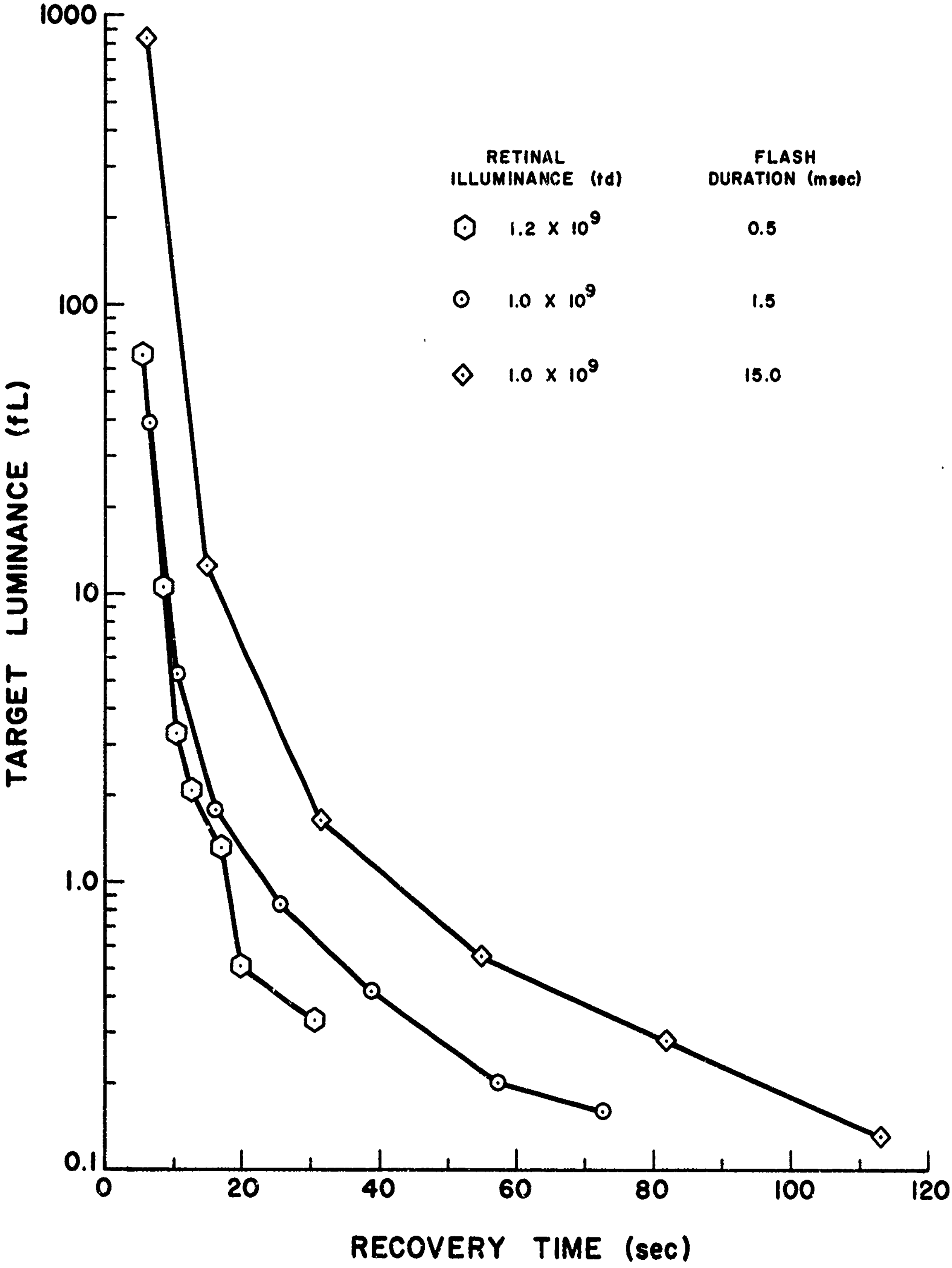

Figure 32. Flashblindness recovery following flashes of intensity and duration as indicated.

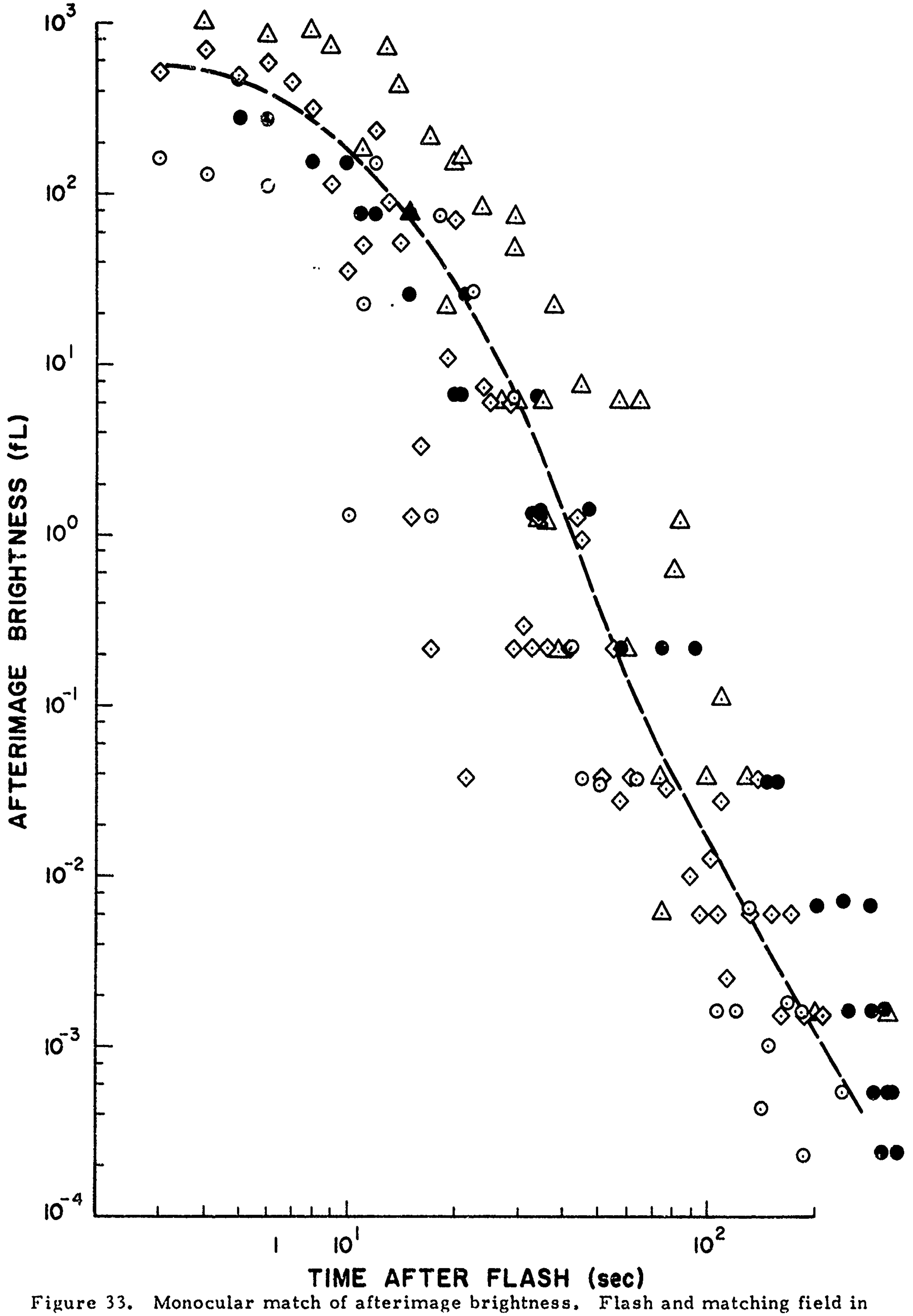

Figure 33. Monocular match of afterimage brightness. Flash and matching field in same eye.

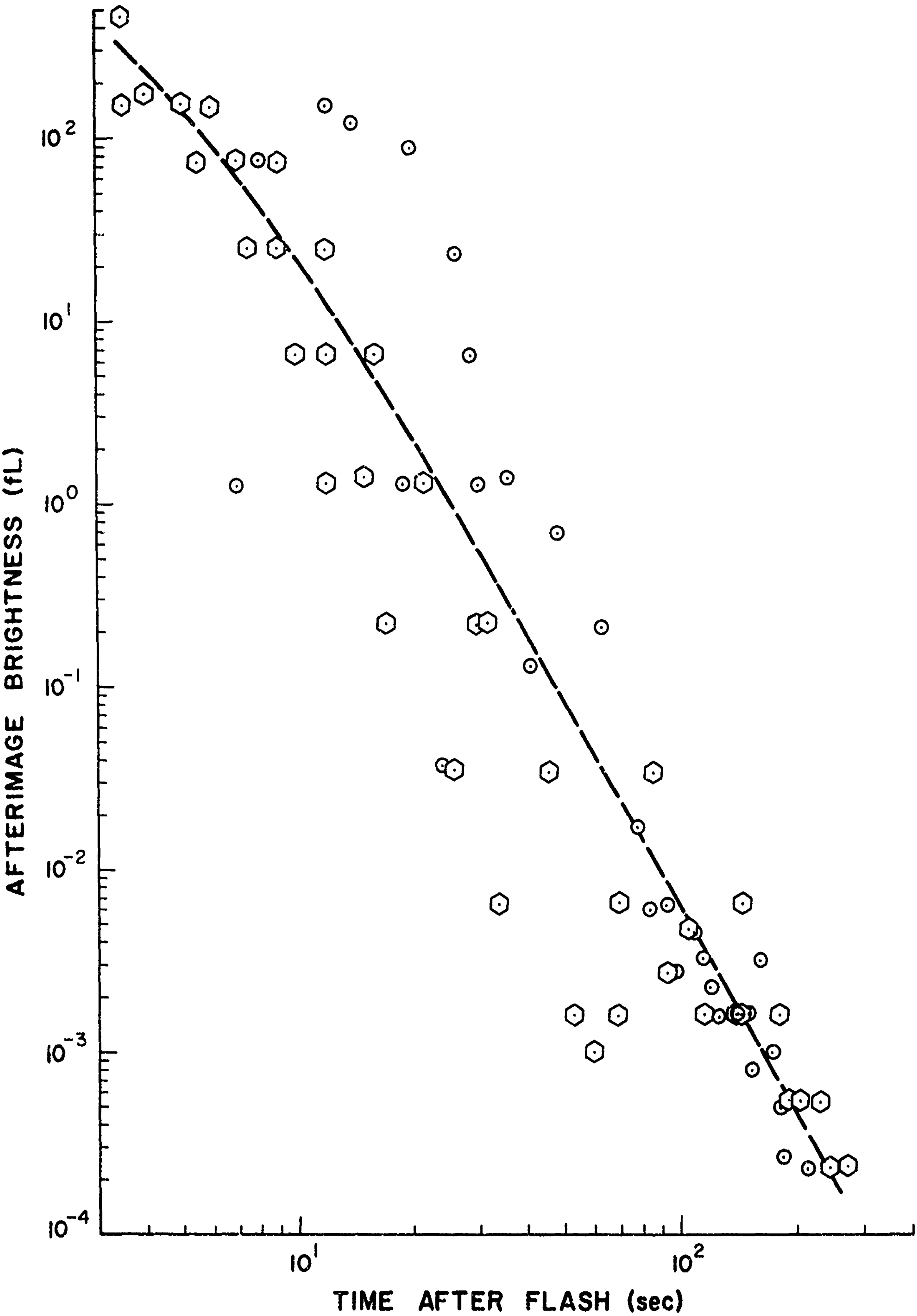

Figure 34. Binocular match of afterimage brightness. Flash and matching field in different eyes.

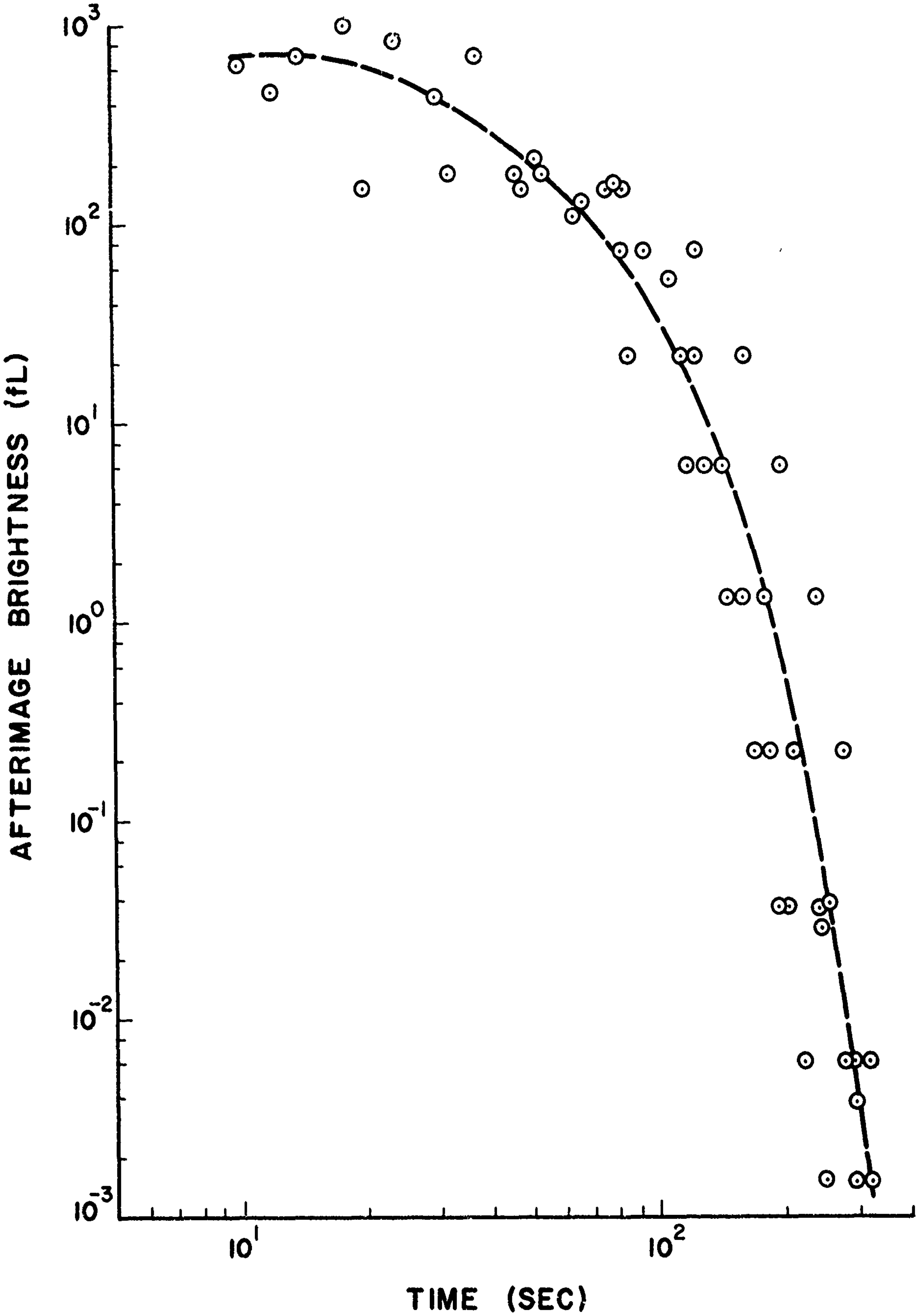

Figure 35. Monocular match by subject CW. Flash intensity reduced by a factor of ten.

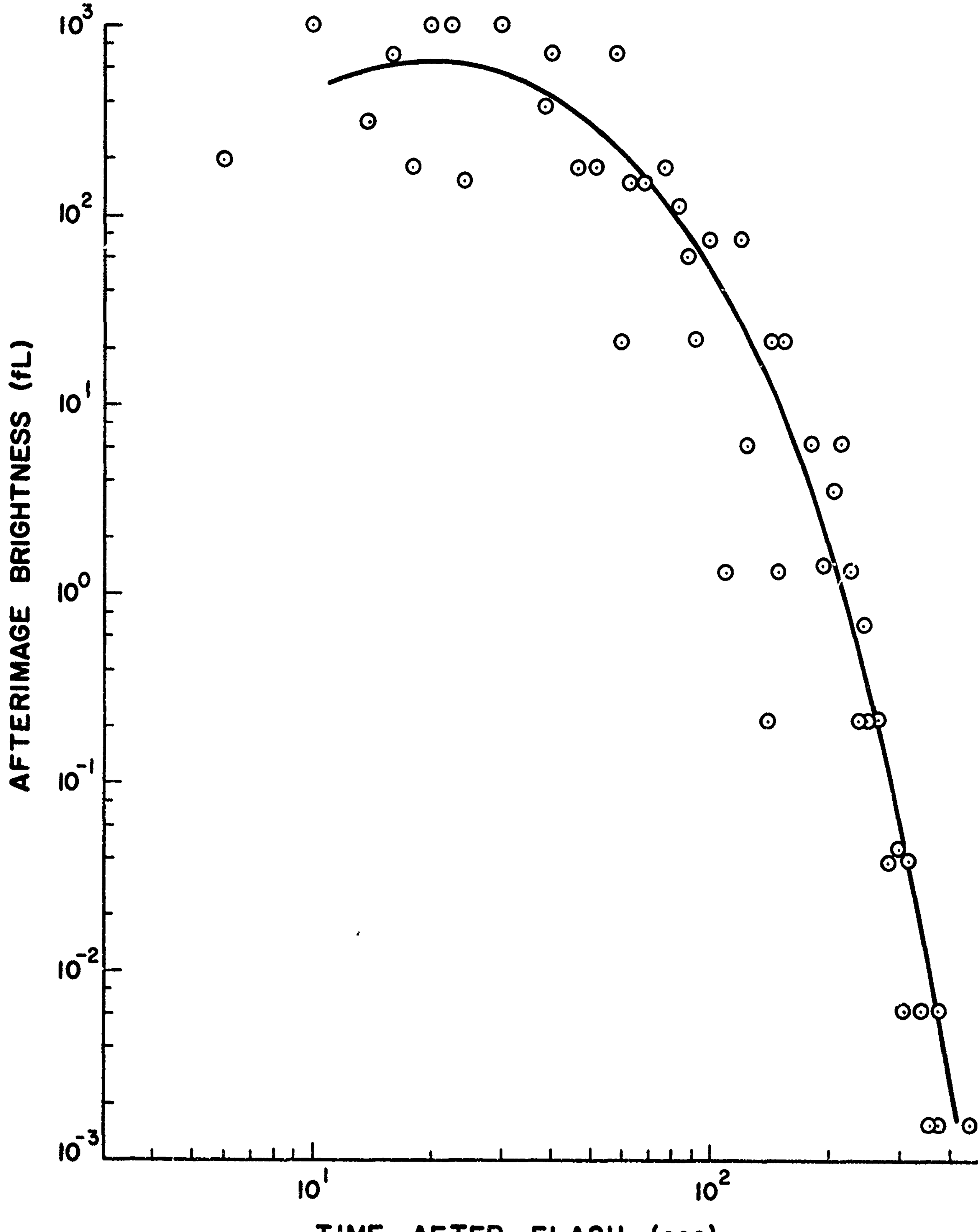

Figure 36. Monocular match by subject CW. Flash at full intensity.

was not included in Figure 33 because of the obvious difference between these data and the matches by the other four subjects. This difference was probably due to the difference in pupil size between CW and the other subjects (see Table I for example). However, there is no reason to believe that a comparison of the two sets of data on subject CW is not valid. At any rate, when these data are compared, there appears to be little or no difference in afterimage brightness following flash of 5.4×10^{10} td and a flash of 5.4×10^{9} td, both presented at a flash duration of 0.5 msec.

3.7.3 The effect of flash source intensity and duration on the ratio of photopigment bleached.

The percent of photopigment bleached was calculated by use of a five-component model of photopigment kinetics developed by Mainster, et al.[2] Table XI lists the flash intensity in retinal illuminance, flash duration, retinal exposure and percent bleach for these flashes. These bleach values are presented in Figure 37 as a function of retinal exposure. It can be seen that all except two values lie very close to the smooth curve of the figure. These two values are for 100 sec and 120 sec exposures and even so they are still not widely different from the other values around the curve.

TABLE XI

Photopigment Bleach as a Function of Retinal Exposure

Retinal Illuminance (td)	Flash Duration	Retinal Exposure (td sec)	% Bleach
2.38×10^{10}	0.8 msec	1.91×10^{7}	100
2.90×10^{11}	0.8 msec	2.32×10^{8}	100
7.80×10^{9}	0.5 msec	3.90×10^{6}	72
3.00×10^{8}	13.0 msec	3.90×10^{6}	72
3.90×10^{7}	100.0 msec	3.90×10^{6}	72
3.90×10^{6}	1000.0 msec	3.90×10^{6}	72
4.12×10^{8}	5.0 msec	2.06×10^{6}	49
6.50×10^{7}	5.0 msec	3.24×10^{5}	10
4.12×10^{7}	5.0 msec	2.06×10^{5}	7
4.20×10^{7}	5.0 msec	2.10×10^{5}	7
1.26×10^{9}	0.5 msec	6.30×10^{5}	19
1.14×10^{10}	0.5 msec	5.70×10^{6}	85
1.00×10^{9}	1.5 msec	1.50×10^{6}	39
9.20×10^{7}	40 msec	3.68×10^{6}	70
1.80×10^{6}	40 msec	7.20×10^{4}	2
9.40×10^{4}	100 sec	9.40×10^{6}	74
3.50×10^{4}	120 sec	4.20×10^{6}	52

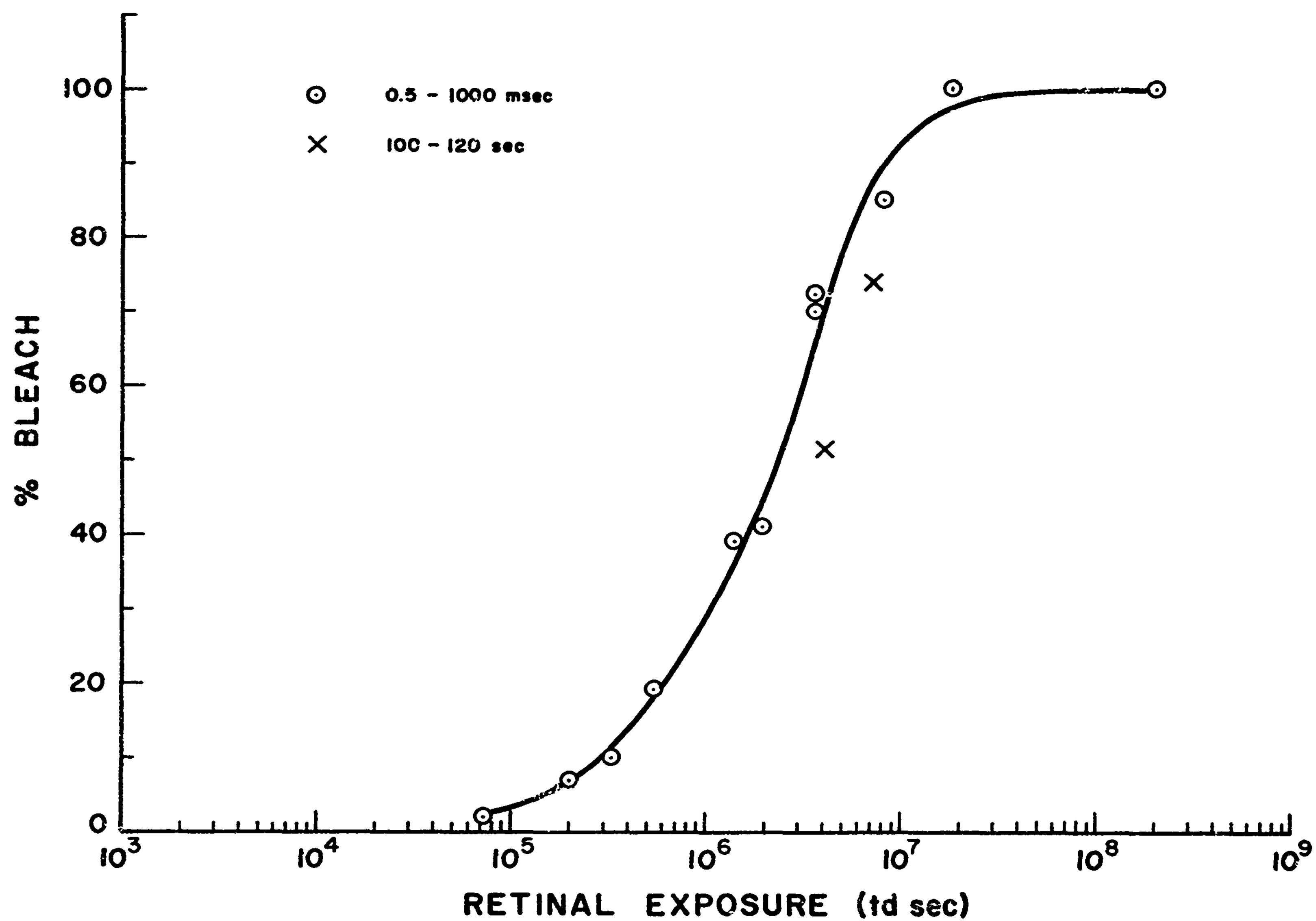

Figure 37. Percent photopigment bleach as a function of retinal exposure.

4. DISCUSSION AND CONCLUSIONS

4.1 Correlation of Flashblindness Recovery Data and Fundus Reflectometry Data.

A comparison of the fundus reflectometry data and flashblindness recovery data obtained during this program indicates that flashblindness recovery is not closely related to photopigment regeneration. The exposures between the two experiments were calculated to produce the same total photopigment bleach. As such, it was expected that the relative positions of the curves would correspond (i.e., either the 40 msec or the 100 sec curve was expected to be above the other consistently in both experiments). However, as a consequence of the data presented graphically in Figure 12, it seems only reasonable to conclude that no quantitative relationship can be established between fundus reflectometry and flashblindness at this time.

4.2 Effects of Preadaptation to High Ambient Light Levels on Flashblindness Recovery Time

Any experiments conducted with high ambient light levels must consider the pupillary contraction during the ambient light exposure. The pupil area must be measured or it must be chemically dilated in order not to vignette the pupillary image of the Maxwelliam optical system. In this experiment, the pupil area was measured and accounted for in the calculation of retinal illuminance.

The highest adapting field luminance used was 5.6×10^3 fL, which is approximately the luminance of white paper in direct sunlight.

Superimposed on this and two other lower adapting fields was a flash of approximately 2.2×10^6 fL or 2×10^7 td-sec. As evidenced by the recovery curves in Figure 11 there was very little effect from the preadapting levels. As a consequence, it must be assumed that the bleaching flash produced virtually a saturation effect. This hypothesis can be substantiated by a study of Figure 37. There appears to be a good correlation between the bleach values and the flashblindness effect produced by a retinal exposure of the same magnitude.

4.3 Foveal Recovery Times as a Function of the Location and Area of the Flash Source Image

4.3.1 Foveal recovery times as a function of flash field location on the retina

Flash image position on the retina has a pronounced effect on foveal recovery times. A study of Table VII will suffice to show that as the flash image is moved from the fovea flashblindness recovery is shortened.

It is apparent that target identification times, although quite rapid following a flash in the periphery, are not unaffected by the flash-that is, they are slower than those to be seen in the

baseline curve. One plausible hypothesis to explain this finding is that the "shock" of such a powerful flash produces a momentary startle response or inattention to the target letter, in spite of the fact that the subject is fully informed as to precisely when the flash will occur. Such an explanation leads to the prediction that this momentary lapse would produce a lengthening in the time to identify the brightest target letter, but that subsequent letters should be identified at rates similar to those of the baseline trials. However, it may be seen that while subjects require additional time to identify the first target, this difference had increased by the seventh target. The results show that the effects of a bright extra-foveal flash upon foveal visibility are more than transient. This may be ascribed to the results of lateral adaptive effects due to (a) lateral neural interactive effects, and (b) light adaptation of the fovea due to stray light within the eye.

A comparison of the central flash with the off-center flashes shows that recovery times are slightly longer following the central flash. Since the central flash recovery times were not shorter than those for the off-center flashes, this indicates that target identification was not more difficult when the letter appeared very close to the edge of the sharply-defined afterimage (an extra contour which might be considered to increase the "complexity"

of the target to be identified). A second factor which may have been involved is difficulty in fixating the point where a letter is expected to become visible, when a large uniform afterimage is centered on the fovea. This factor might be reduced when the afterimage is so situated that a slight sideways glance can serve to localize the exact position of the letter.

There appears to be no effect ascribable to the "clock" positions of the flashes about the fovea, but perhaps with more data, such might be discovered.

4.3.2 Foveal recovery time as function of flash image size

Foveal recovery does not appear to be strictly a function of flash image size as long as the flash image is larger than the fovea. The response in this case is one of looking "around' or "through" the afterimage. If the flash luminance is held constant, then a rather stable recovery time may be obtained for all task identifications made through the afterimage no matter what the flash image size. However, it would be erroneous to say that the recovery time does not increase as flash image size increases. Reference to Table VIII will show that this does in fact occur to a certain extent but it should be noted that the maximum recovery times are attained from 2.5° through 3.0°.

It seems clear that the strategy for the earliest target recognition depends upon the visual detail size of the task and upon the particular flash diameter employed. Regardless of the size of the flash, our data show that 20/40 target identification could be made most quickly by looking around the afterimage. When the flash was less than three degrees in diameter it was seen that most task identifications were made around the afterimage. For a flash larger than three degrees, most task identifications were made through the afterimage.

The implications are that if a subject knows the size of the flash image and the size of his visual task, he may then make some assessment as to whether to try to look "around" or "through" the afterimage. For example, the limit for useful 20/40 visual acuity is 1.5° to 2.0° from the fovea,[7] from which it follows that a subject cannot be expected to resolve a 20/40 target around a centrally fixated 5° flash. If the subject does not know this or the size of the afterimage he may continue to "look around" the afterimage but by doing so no target identification will be made. On the other hand, if he continued to attempt fixation through the afterimage, his foveal vision would most certainly

enable him to preceive the task after a period of dark adaptation. It is true that this process might take some time but at least the task would eventually be identified whereas it would not be identified at all around the foveally centered afterimage.

4.4 Intensity x Time Relationships

4.4.1 Time-Intensity relationship for equal energy flashes

The concept of reciprocity is that equal effects will be obtained from flashes of equal time-intensity relationships. This was not evident for the flash pulse range and intensities utilized in the subject experiments. Equal energy flashes ranging from 0.5 msec to 1000 msec in duration were investigated in three series of experiments. Equal recovery times were not obtained for any of these pulse durations. In fact, there was an ordered succession from the slowest pulse (1000 msec) to the fastest pulse (0.5 msec) with the longest recovery times being shown for the 0.5 msec flash duration.

4.4.2 Equal bleach relationships

Two flash durations were investigated in an attempt to characterize equal photopigment bleaches. The flash exposure was designed to bleach (a) equal concentrations of total cone photopigment and

(b) equal concentrations for photoproduct C. Equal flashblindness recovery was not obtained across any combination of the conditions presented in Table IX.

The result of this experiment was clearly an indication that flashblindness recovery is not simply related to the calculated quantity of photopigment bleached by exposure to bright light. This relationship, if one exists, cannot be ascertained from these data at this time.

4.5 Foveal Dark Adaptation with Acute and Gross Targets

4.5.1 Foveal dark adaptation following short flash exposures

The general form of foveal dark adaptation was shown to be quite consistent in Figure 19. Measurements of adaptation to three different target configurations, including simple, single line targets are included in this figure.

4.5.2 Foveal dark adaptation following extended retinal exposures

A comparison of Figure 19 and 20 reveals that the initial phase of foveal dark adaptation following a steady adapting light is much faster than that following a flash of approximately comparable bleach value. However, the latter phase of dark

adaptation seem to be quite similar for both exposures.

The reason for the pronounced delay in recovery time following a brief flash may probably be partially ascribed to the initial shock of receiving such a flash exposure within so short a time. Of course, the flash exposure is much brighter and the initial bleach is much greater than that of the steady exposure but the effect seems to be related to more than merely the quantity of bleach. Otherwise the recovery curves after cessation of the bleaching exposure would certainly be more nearly identical due to the fact that the same amount of photopigment was bleached in both experiments.

4.6 Variability of Interindividual Flashblindness Recovery Times.

4.6.1 Intersubject variability for a complete flashblindness recovery curve

The tendency, in individual subjects, seems to be one of a continued increase in variability as the target luminance decreases. Such an increase would be expected until the subject reached his absolute visual threshold. However, target luminance values approaching threshold were not investigated during this experiment.

Intersubject variability is seen to increase rapidly beginning with a target luminance of about 100 fL. As the target luminance decreased, an approximate leveling occurred at about 6 fL. However, the fact that the data are presented on a log scale must be considered when any quantitative assessments are to be made by reference to the plotted curve.

4.6.2 Intersubject variability to a single fixed luminance value

The distribution of target identification times through the after-image is very close to the standard bell curve of a "normal" distribution pattern. This type of response is to be expected in any relatively large sample of a population. However, the fact that the "around" mode of identification is so skewed indicates that an absolute limit for identification times is being approached. This limit is made up of subject neural response time, shock artifact from the flash, task recognition and finally motor response, although perhaps not in that order.

Calculation of the standard deviations for each mode of identification and for the combined responses revealed less variability in identification times "around" the afterimage than "through" the afterimage.

Exposure to the 2.5° field resulted in greater variation than was noted with the other flash fields. However, it is not known if this represents a significant trend.

4.7 The Effect of Flash Source Intensity and Duration on Recovery Times, Afterimage Brightness and Ratio of Photopigment Bleached

4.7.1 The effect of flash source intensity and duration on recovery times

4.7.1.1 Reciprocity

Generally, manipulation of the flash source intensity and duration to achieve the same effect has not been successful. The effects have been more a function of flash intensity are evident in that the larger recovery times have followed the shorter more intense flashes. This subject was also discussed in Section 4.4.1.

4.7.1.2 Flashes of equal duration

As the retinal illuminance of a flash increases, a point will be reached where little further visual effect will be seen. Of course, as the illuminance continues to increase, the probability of sustaining permanent damage to the retina also increases. However, the illuminance values used in the experiment were not of such a damaging magnitude.

In the case of Figure 28, the 6.5×10^7 td curve shows an increase in recovery time of about 1.6 over the 4.1×10^7 td curve. This corresponds to an increase of 1.6 in the flash intensity. The other curves of Figure 27, 28 and 29 all represent flashes at least 10 times as intense as the dimmest flash represented each graph but in no case do the recovery values increase by 10 times. It is likely that at these flash intensities, so much photopigment has been bleached that any increase in retinal illuminance is essentially ineffective as a further bleaching source. There are effects other than photopigment bleach but little is known about them at the present time.

4.7.1.3 Flashes of approximately equal intensity

Flashes of approximately equal intensity but different durations produce recovery effects that are generally ordered from the shortest duration and fastest recovery to the longest duration and slowest recovery. There is a rather obvious correlation between flash pulse duration and recovery time; that is, as the flash duration increases, the recovery time increases. This correlation has not been quantified but it definitely is not

linear in the range of flash intensities used in this experiment.

4.7.2 The effect of flash source intensity and duration on afterimage brightness

The decay of the afterimage does not follow the same time course as visual acuity recovery. Visual acuity recovery is very fast when compared to the decay of the afterimage. In fact, visual identification of a specific target luminance is made before the afterimage has decayed to that luminance level. An explanation of this phenomenium is not available from these data.

Apparently the afterimages associated with retinal illuminance values of 10^{10} and 10^{9} td for 0.5 msec begin to approach the maximum brightness that can be accomodated by the visual system. This is demonstrated by the fact that a decrease in retinal illuminance by a factor of ten causes little or no change in the apparent afterimage brightness.

The form of the curves indicates a brightness decay which is approximately fitted by a power function. However, the initial portion lasting for the first 10 to 20 seconds cannot be fitted by this function. It is apparent that the precipitous fall in the visual acuity threshold during this same period is not related to the decay of the super-imposed afterimage, but to some other mechanism.

This period in the flashblindness situation is hypothesized to be one of rapid functional neural reorganization.

4.7.3 Ratio of photopigment bleached

To calculate photopigment bleach, the retinal illuminance and flash duration must be known. When these values were expressed as retinal exposure and plotted against percent bleach it was clear that the resulting function was quite stable as long as the flash durations were 1000 msec or shorter. The two long term exposures (100 and 120 sec) did not fit the curve in Figure 37 extremely well. This result was expected because previous work had shown dissimilarties between the effects of long and short flash duration.

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